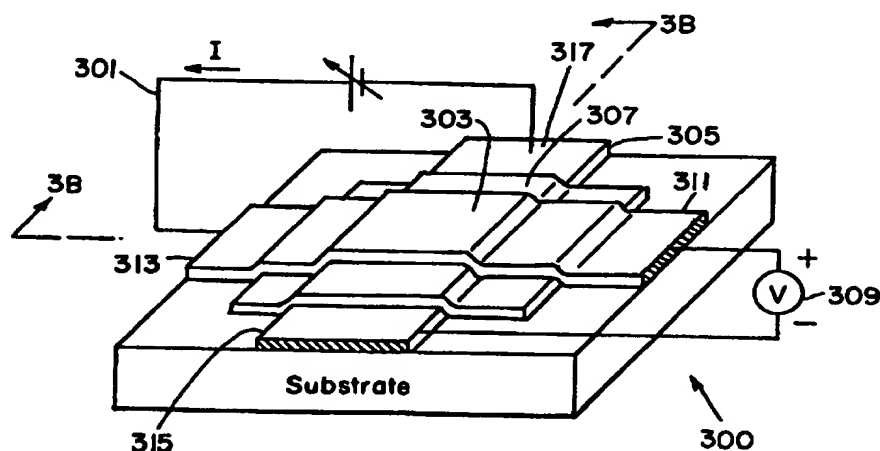




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(54) Title: GEOMETRICALLY ENHANCED MAGNETORESISTANCE IN TRILAYER TUNNEL JUNCTIONS



(57) Abstract

Ferromagnetic-insulator-ferromagnetic trilayer junctions show magnetoresistance (JMR) effects ranging from about 16 % to several hundred percent at room temperature. Larger effects are observed when the actual tunneling resistance (R_T) is comparable to electrode film resistance (R_L) over the junction area in cross-geometry junction measurements. The geometrically enhanced large JMR can be qualitatively explained by the nonuniform current flow over the junction area when R_T is comparable to R_L in the cross-geometry junction structure. For a fixed junction area, the effective junction resistance (R_J) can be varied from less than 1 ohm to several kilohms by controlling the thickness of the insulating layer or by appropriately selecting ferromagnetic films. The trilayer tunnel junctions of the present invention are nonvolatile, stable and are reproducible.

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GEOMETRICALLY ENHANCED MAGNETORESISTANCE
IN TRILAYER TUNNEL JUNCTIONS

RELATED APPLICATION

This application claims priority to U.S. Provisional Application No. 60/015,798 filed on April 17, 1996, and is a Continuation-in-Part of and claims priority to U.S. Application No. 08/747,152, filed November 8, 1996, the teachings of which are incorporated herein by reference in their entirety.

10 GOVERNMENT FUNDING

This invention was made with Government support under Contract Nos. N00014-92-J-1847 and DMR-9423013 awarded by the Office of Naval Research and the National Science Foundation, respectively. The Government has
15 certain rights in the invention.

BACKGROUND OF THE INVENTION

Electron tunneling is a quantum phenomenon in which electric current can pass from one electrode through a thin insulating barrier layer into a second electrode.
20 This three layer system of electrode, barrier and counter-electrode is referred to as a trilayer tunnel junction device. Where the electrodes are made of ferromagnetic material, a ferromagnet-insulator-ferromagnet (FM-I-FM) trilayer tunnel junction is
25 formed. The intervening thin insulating layer is known as "tunnel barrier". The current flowing through a tunnel junction varies in accordance with the relative magnetization (M) direction of the FM electrodes which affects the resistance of the junction. The junction
30 resistance increases when the magnetization of one FM becomes antiparallel to that of the other FM and decreases when they become parallel to one another.

Change in resistance of a magnetic material due to applied magnetic field is referred to as

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"magnetoresistance." For resistance change in a tunnel junction, the term "junction magnetoresistance" (JMR) is used, and is typically expressed in percent-ratio.

Julliere, Phys. Lett. 54A, 225 (1975), proposed an
5 explanation for the change in junction resistance with change in magnetization direction. The explanation given in the article is based on the conduction electron spin polarization values of the FM electrodes. According to this model, the ratio of the change in the
10 tunnel junction resistance to a peak tunnel junction resistance is given by:

$$\Delta R/R = (R_a - R_p)/R_a = (G_p - G_a)/G_p = 2P_1P_2/(1+P_1P_2)$$

(1)

Here R_p and R_a represent the junction resistances when
15 the magnetization direction of the electrodes are parallel and antiparallel, respectively, and G_p and G_a are the equivalent conductances. P_1 and P_2 are the conduction electron spin polarization values of the two FM electrodes as measured by spin-polarized tunneling
20 experiments with superconductors. Ideally, for ferromagnet materials having spin polarizations of 40% and 34% the above expression yields a theoretical JMR ($\Delta R/R$) of 24% in tunneling conductance due to the change in magnetization directions of the electrodes.

25 The ideal result given by the above mathematical expression neglects, however, limiting factors, such as, domain walls in the junction area, interfacial and barrier spin scattering, direct coupling between the two FM films, and surface degradation of FM films. In
30 practice, all of these factors and perhaps others significantly impact the expected effect.

Various scientific groups experimenting mainly with nickel oxide (NiO) and aluminum oxide (Al_2O_3) as barriers between nickel (Ni) and cobalt (Co) electrodes have
35 reported a small JMR in FM-I-FM devices. However, in

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most of these cases, the observed JMR's were between 2-6% at 4.2K at best, and typically only fractions of a percent at room temperature (295K). Recent experimental work by Miyazaki et al., J. Magn. Magn. Mater. 126, 430
5 (1993), showed a JMR of 2.7% at room temperature.

Scientists, including Miyazaki et al., for years, have known in theory about the fundamental dynamics of the tunnel resistance arising from conduction electron spin polarization. However, the past efforts in this
10 area have failed to produce the level of change in the tunneling resistance adequate for any practical or effective use. To be of any significance, the JMR should be at least 10% in a typical application.

Consequently, a need exists for an FM-I-FM trilayer
15 junction construction in which the magnitude of the junction resistive change is at least 10%. Tunnel junction devices implicate a wide range of practical uses. In particular, any devices requiring memory or a sensor element can be considered.

20 SUMMARY OF THE INVENTION

The present invention relates to a magnetic trilayer tunnel junction device having junction resistance and fabrication methods thereof. The present state of the art for read-heads now found in computers
25 uses a property of magnetic materials known as anisotropic magnetoresistance (AMR), or more recently, giant magnetoresistance (GMR). But these materials require about 60 alternating layers of ferromagnetic and non-magnetic thin metal films in which the thickness of
30 each layer must be precisely controlled.

In contrast, the tunnel junction magnetoresistance (JMR) device of the present invention comprises just three layers: two ferromagnetic films separated by an ultra thin insulating layer. The resulting device is
35 thinner (less than 50 nanometers) and more sensitive than a GMR device, yet it does not require the level of

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precision control that a GMR device typically requires. Since the read-head of a computer storage device can be greatly reduced in dimensions with the use of the JMR device of the present invention, the amount of data a disk can hold is, in effect, significantly increased.

In a preferred embodiment, the junction device of the present invention comprises a first electrode having a first independent magnetization direction, a second electrode having a second independent magnetization direction, and an insulator between the first and second electrodes to form a trilayer tunnel junction. The resulting junction has an effective junction resistance which essentially constitutes a difference between the junction resistance and a parasitic resistance contributed by the electrodes near and throughout the junction. A small excitation of electromagnetic energy applied to the junction reverses at least one of the magnetization directions of the electrodes and causes a change in the junction resistance by at least 10% at room temperature with respect to the effective resistance.

The preferred embodiment further comprises electrical contacts connected to each of the first and second electrodes that extend beyond the junction area and are electrically continuous to the electrodes and form non-overlapping region with respect to the junction.

In the preferred embodiment, the first and second electrodes are typically ferromagnets (FM), each having an electron spin polarization value of about 0.5 or less. In other embodiments of the invention, the first and second electrodes can be half-metal ferromagnets (HMF). For an HMF, a higher electron spin polarization value of up to 1.0 can be allowed. In yet other embodiments, a combination of FM and HMF can be used to form tunneling devices.

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In the preferred embodiment, the effective junction resistance of the device can be varied by controlling either the parasitic resistance or the junction resistance. The parasitic resistance can be controlled
5 by selecting the electrodes of different thickness or electron spin polarization.

The junction resistance can be controlled by changing the thickness of the insulator layer. Preferably, the thickness of the insulator layer ranges
10 from about 2 angstroms to 30 angstroms. The insulator layer is formed first by providing a thin precursor metal film selected from a group consisting of Al, Mg, Ta, Ti, Y, and Si. The thin film layer is then reacted with a reactive gas, typically anywhere from 2 to 110
15 seconds, to form a tunnel barrier. The thickness of the resulting barrier layer depends on the amount of the reaction duration applied. Preferably, the insulator is a surface-reacted metal film selected from a group consisting of Al_2O_3 , AlN , Si_3N_4 , MgO , Ta_2O_5 , TiO_2 , and
20 Y_2O_3 .

In a preferred embodiment, where the parasitic resistance is greater than the junction resistance, a negative effective resistance can result. For certain applications, therefore, the materials of the tunneling
25 device can be controlled so that the effective junction resistance is initially negative then changes to become positive when the electromagnetic energy is applied to the junction.

In a preferred embodiment, an NiO film is deposited
30 onto the second (top) electrode to provide an exchange biasing layer such that the junction magnetoresistance for the junction device is asymmetric with applied magnetic field. The NiO film further provides corrosion resistance for the FM-I-FM junction device.

35 The device of the present invention can be implemented in a system for diagnosing biological tissue samples. The system generally comprises a sensor for

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detecting any malignant portions of a biological tissue sample, which includes a matrix array of trilayer tunnel junction devices of the present invention as described above, and a display station connected to the sensor for
5 receiving image signals to display color-mapped images of the sample to locate and diagnose the malignant portions of the sample. The tissue sample is pre-treated with a chemical coating containing a magnetic content which is essentially absorbed by healthy
10 portions of the sample, and allows the sensor to distinguish the healthy portions from the malignant portions of the sample.

Other applications of the present invention include a computer storage device. The device generally
15 comprises a magnetic disk for storing binary data, and a sensor-head for reading the data from the disk which includes the trilayer tunnel junction device of the present invention as described.

In the preferred embodiment, the trilayer tunneling
20 device is fabricated by providing a flat smooth substrate in a vacuum evaporation chamber. The substrate is initially cooled by placing it on a liquid-nitrogen cooled metal surface. A thin seeding layer is overlaid onto the substrate to provide a basis for the
25 device. The first (bottom) electrode is then deposited onto the seeding layer, followed by a thin precursor film of the insulating layer. Preferably, the precursor film is then gas reacted to form a tunnel barrier. Lastly, the top electrode is deposited on the insulating
30 layer such that a region where the bottom and top electrodes overlap, separated by the insulating layer, forms a tunnel junction.

Preferred methods of depositing the electrode or the insulating film layer include sputtering, such as
35 the radio frequency, direct current, or the ion beam magnetron sputtering.

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Ideally, the metal film of the insulating layer is completely reacted by the reactive gas without causing reaction to the first electrode below, leaving only molecules of the reactive gas as the insulating layer.

5 Preferably, however, the upper surface portion of the metal film is reacted with the reactive gas, leaving a portion of the metal film in contact with one side of the bottom electrode below. This keeps the top surface of the electrode clean, free of any surface corrosion.

10 In another embodiment, the ferromagnet electrodes and the metal film of the insulating layer can be either sputter deposited or evaporated, and the metal film is reacted with a reactive gas by glow discharge prior to depositing the top electrode. In either event,
15 preferably, the first and second electrodes are deposited in a presence of an applied magnetic field to improve magnetic field response characteristics of the tunnel junction.

The above and other features of the invention
20 including various novel details of construction and combinations of parts will now be more particularly described with reference to the accompanying drawings and pointed out in the claims. It will be understood that the particular devices and methods embodying the
25 invention are shown by way of illustration only and not as limitations of the invention. The principles and features of this invention may be employed in varied and numerous embodiments without departing from the scope of the invention.

30 BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic cross sectional diagram of a typical ferromagnet-insulator-ferromagnet trilayer junction in accordance with the invention.

Figure 2 is a set of plots showing change in
35 resistance (JMR) as a function of applied magnetic field

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H in Oersted at 295 K for a ferromagnet pair and a FM-I-FM trilayer junction.

Figures 3A and 3B depict the four-terminal technique and the current path of a geometrically-enhanced FM-I-FM trilayer tunnel device in accordance with the present invention.

Figures 4A and 4B graphically illustrate current distribution in geometrically-enhanced FM-I-FM trilayer tunnel junctions of the present invention.

Figures 5A and 5B illustrate temperature variation of JMR of the FM-I-FM trilayer tunnel junction device of the present invention.

Figures 6A to 6C illustrate the possible device geometries of the geometrically-enhanced trilayer tunnel junction device of the present invention.

Figure 7 is a magnetoresistance response at room temperature of a $\text{CoFe}/\text{Al}_2\text{O}_3/\text{NiFe}$ junction in the kilo-ohm range.

Figure 8 is a magnetoresistance response at room temperature of a $\text{CoFe}/\text{Al}_2\text{O}_3/\text{NiFe}$ junction in a low resistance range.

Figure 9 is a negative magnetoresistance response of a $\text{CoFe}/\text{Al}_2\text{O}_3/\text{NiFe}$ junction.

Figure 10 is a magnetoresistance response at room temperature of a $\text{CoFe}/\text{Al}_2\text{O}_3/\text{NiFe}$ junction in the mili-ohm range illustrating a resistive polarity switch.

Figure 11 is a magnetoresistance response in the mili-ohm range of a $\text{CoFe}/\text{AlN}/\text{NiFe}$ junction showing the hysteresis property of a tunnel junction device.

Figure 12 is schematic prospective drawing of a memory device according to the invention.

Figure 13 is an enlarged view of the disk surface coated with FM-I-FM memory cells.

Figure 14 is a sectional view of the multi-layer disk surface including a layer of FM-I-FM memory cells.

Figure 15 is a schematic drawing of a sensor device according to the invention.

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Figure 16A is a schematic/prospective drawing of a magnetic storage disk drive system.

Figure 16B is an enlarged view of a read-write sensor head according to the invention.

5 Figures 17A to 17C illustrates a medical imaging device in accordance with the present invention.

Figure 18 graphically illustrates the effect of depositing ferromagnet layers under applied magnetic field.

10 Figures 19A to 19C graphically illustrates the effects of ferromagnets having different coercive forces.

Figure 20 is a schematic cross-sectional diagram of an FM-I-FM trilayer junction with an exchange biasing
15 layer on the top FM layer in accordance with the invention.

Figures 21A and 21B illustrate the exchange biasing effect on the FM-I-FM trilayer junction device of Figure 20 at different temperatures.

20 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the drawings, Figure 1 describes a preferred ferromagnet-insulator-ferromagnet FM-I-FM trilayer tunnel junction device of the present invention,

25 wherein the current flowing through the device is represented by "I" and the voltage across the junction by "V". An electromagnetic energy source 16 affects magnetization direction 28 for each ferromagnet electrode by applying a small magnitude of magnetic
30 field across the junction. To affect magnetization direction in each of the FM electrodes 12, 10, the plane of the trilayer tunnel junction 20 may be oriented in any position with respect to the direction of the applied field 16.

35 An example of a preferred method of fabricating the FM-I-FM thin film planar trilayer tunnel junction 20, as

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shown in Figure 1, involves a vacuum evaporation process in which an aluminum oxide (Al_2O_3) is used as the insulating layer. In a vacuum evaporation chamber (not shown), a substrate 22 having a flat smooth upper surface 22a is initially cooled by placing the substrate in contact with a liquid-nitrogen cooled metal surface. The cooled surface 22a is then covered with a layer of about 10 Å of a suitable seeding layer 24, such as glass or silicone (Si). Next, a first FM metal film 12 of about 80 Å of thickness is laid on the seeding layer. An aluminum (Al) precursor film 14 of about 12 to 18 Å of thickness is then deposited over the entire top surface of the first FM layer 12. After bringing the substrate to room temperature, the Al precursor film 14 is oxidized by glow discharge to form an Al_2O_3 insulating tunnel barrier layer. This procedure oxidizes about 12-14 Å of the original Al film. Continuing in a vacuum, (cross strips of) a top FM electrode 10 of about 100 to 300 Å thick are laid on the insulating barrier layer 14 at room temperature.

The tunnel junction resistances of a device 20 can range from hundreds of ohms to tens of kilo-ohms, depending on the duration of the glow discharge and the type of FM materials used.

Preferred materials for the FM electrode pair in a trilayer tunnel junction include cobalt iron (CoFe) for the first FM film layer and either cobalt (Co) or nickel iron (NiFe) for the second counter FM layer. It is preferred that the FM layers have high conduction electron spin polarization (P) of 0.3 or greater. Preferably, the layers are formed by a vacuum evaporation process but other suitable process may be substituted, such as sputtering, electroplating or laser ablation. Preferably the substrate is glass, but other suitable materials include silicon, germanium, gallium arsenide wafers, and mica. The preferred insulator materials include like magnesium oxide and aluminum

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oxide. Preferably, the material for seeding layer provides high melting point of about 1000 degrees Celsius or greater. Preferred seeding layer materials include silicon, germanium and titanium oxide.

5 Figure 2 illustrates the magnetic field (H) dependence of junction resistance for a CoFe/Al₂O₃/Co junction. In Figure 2, the percent ratio of change in junction resistance to peak junction resistance $\Delta R/R$ of a CoFe/Al₂O₃/Co trilayer junction as a function of H is
10 shown in curve (a). The arrows on the junction curve (a) indicate the magnetization directions of the two ferromagnet films.

Curves (b) and (c) show the relative variation in resistance of the bottom (CoFe) and top (Co) FM films,
15 respectively, per se due to magnetic field at room temperature. In particular, these curves determine the coercive field magnitude (or "coercive force") (H_c) defined as the magnitude of field intensity required to change the magnetization direction in each FM electrode.
20 In (c), H_c for Co is approximately 100 Oe, whereas H_c for CoFe in (b) is significantly greater at 200 Oe. In (a), the measured JMR ($\Delta R/R$) of the tunnel junction CoFe/Al₂O₃/Co is 10.6% at room temperature.

The field dependence of in FM-I-FM tunnel junction
25 resistance as shown in Figure 2 can be explained qualitatively based on individual FM curves (b) and (c). At high fields (beyond the H_c of the FM films), the magnetization of the two FM films are fully saturated and aligned in the same field direction. The tunneling
30 probability and, hence, the current is high. As H decreases towards zero and changes sign, the magnetization direction of the film with lower H_c (top FM) reverses its direction, whereas for the film (CoFe) which has higher H_c (bottom FM), its magnetization
35 direction remains the same. In this field range (50 Oe to 250 Oe), the magnetization orientation of one film is antiparallel (opposite) to the other, the tunneling

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probability is lowered, the junction resistance increases rapidly, and the tunnel current decreases accordingly. Upon raising the field further in the reverse direction, the magnetization direction in the second film also reverses, becoming parallel to the first film, and the junction resistance begins to decline rapidly.

A significant JMR of over 10% observed at room temperature, as shown in Figure 2 was attained from FM-I-FM junction devices having relatively high junction resistance (R_J), in the kilo-ohm ($k\Omega$) range, and large junction surface area, in the range of 10^3 to 10^4 cm^2 . As the junction area is decreased to a few square microns for a typical device application, the junction impedance can reach on the order of several mega-ohms ($M\Omega$), creating noise problems.

For many applications, however, the preferred junction impedance is in the range of one to a few kilo-ohm. In accordance with the methods of the present invention, a lower tunnel junction resistance can be achieved by controlling the thickness of the insulator layer and, to a lesser extent, the thickness and the material content of the FM electrodes.

Figure 3A illustrates a technique for reassuring tunnel junction resistance of a geometrically enhanced FM-I-FM tunneling device. The technique is commonly referred to as the "four terminal technique" (FTT) in which the current source 601 is connected to the free ends of the top and bottom FM electrodes 303, 305 of the device 300 and, similarly, the two electrical leads of a volt meter 309 are connected to the opposite free ends of the top and bottom electrodes 303, 305. The "effective" or measured junction resistance, R_J , can be determined from the relationship

$$R_J = V/I.$$

In Figure 3A, current (I) from the source 301 originating from the top FM electrode 303 flows through

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the junction area into the bottom electrode 305. Again, the junction area is defined as the region where the top and bottom electrodes overlap, the two electrodes being separated by a tunnel barrier or an insulator layer 307.

5 The device 300 shown in Figure 3A is another preferred embodiment of the present invention which is different from the more conventional trilayer tunnel junction described in Figure 1 and which provides a significantly improved JMR response over the conventional device.

10 In Figure 3A, two strips of FM electrode layers 303, 305 are cross-layered on either side of an insulator to form a tunnel junction area in the center, leaving the four ends of the electrodes non-overlapping. In Figure 3B, it is illustrated that the current (I) from the source 301 flows out from one end of the top electrode 303, through the junction area, crossing through the insulator layer 307, and flows out through one end of the bottom electrode 305 to complete a closed-loop current path. An important artifact of this electrical arrangement in a cross-geometry tunneling device is that the current flowing through the junction area is non-uniformly distributed, and, therefore, the effective junction resistance (i.e., measured $R_J = V/I$) does not reflect the "true" junction resistance, R_T .

25 Accordingly, the device of the present invention forming cross geometry includes non-trivial resistance, referred to herein as "lead resistance", R_L , originating from the portion of the film electrodes near and throughout the junction area. The effects of the lead resistance become quite significant particularly when the device is controlled to produce the true junction resistance (R_T) comparable or even smaller than R_L . Although the actual relationship between R_T , R_J and R_L for the device forming cross geometry is unknown, a simple resistance network model provides:

$$R_J = R_T [1 - f(R_L/R_T)],$$

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where $R_J < R_T$, and $f(R_T/R_L)$ forms a parasitic resistance whose magnitude (Ω) depends on the relative values of R_T and R_L .

From this model, an "apparent" JMR can be derived
5 as the ratio of change in the true junction resistance
to the apparent junction resistance $\Delta R_T/R_J$. Also, from
the above relationship, for $f(R_T/R_L)$ comparable to R_T ,
small or even negative R_J can be attained, and thus a
large apparent JMR (%) can be realized. Additionally,
10 for a certain range of magnetic field excitations, the
measured junction voltage or resistance can change
polarity, operating as a bipolar switch. Figures 4A and
4B graphically describe junction areas of two different
cross-geometry tunneling devices, having the non-uniform
15 current distribution effect. Figures 4A and 4B
demonstrate that this current flow is substantially
greater in the lower left position of the junction
surface, and is gradually reduced in the upper right
portion of the junction. It follows that the resistance
20 of the junction area is also non-uniform. In Figure 4A
the true junction resistance, R_T is 60 Ω . However, the
measured junction resistance R_J is 32 Ω . The lead
resistance is determined as $R_L = 100 \Omega$. Similarly, the
device in Figure 4B shows $R_T = 12 \Omega$, $R_J = -8 \Omega$, and $R_L =$
25 100 Ω .

Figures 5A and 5B illustrate the temperature
dependence of JMR in the geometrically-enhanced tunnel
junctions of the present invention. The fact that the
conventional tunneling junctions of the present
30 invention yield a significantly greater JMR at
temperatures below room temperature (275 K) was
demonstrated in a U.S. application Serial Number
08/407,761, which is incorporated herein by reference.
In Figures 5A and 5B, it can be seen that the JMR of a
35 geometrically-enhanced CoFe/Al₂O₃/NiFe device doubles at
77 K (Figure 5B), and confirms that these devices behave
consistently with the conventional tunneling junctions.

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Figure 6A illustrates other possible tunneling device geometries for enhancing JMR responses. In another preferred embodiment, devices in which the top electrode nearly exactly overlaps the bottom electrode may also be made to exhibit non-uniform current distribution and manifest the lead resistive effect in the junction area. In Figure 6B, the top and bottom electrodes 622, 624 of a FM-I-FM device essentially overlap to form a junction area. Points of electrical contact 620, or the lead portions of the electrodes, however, form non-overlapping regions external to the junction area. In order to attain the desired lead resistive effect, the point of electrical contact must be physically continuous with respect to the remaining portion of the electrodes constituting the junction area.

JMR's taken at room temperature for four different ranges of nominal junction resistance (R_J) are shown in Figures 7 to 10. As R_J decreases from kilo-ohm (Figure 7) to milli-ohm (Figure 10), the apparent JMR ($\Delta R_T/R_J$) increases significantly going from 16.2% to 324%. Figure 7 shows a magnetic response at room temperature of a geometrically-enhanced cobalt iron/aluminum oxide/nickel iron trilayer tunneling device having nominal R_J of about 2.6 kilo-ohms. The device in Figure 7 includes a cobalt-iron ferromagnet layer of 120 angstroms in thickness, an aluminum-oxide insulator layer of 12 angstroms in thickness, and a nickel-iron ferromagnet layer of 200 angstroms in thickness. The response in Figure 7 shows a JMR of about 16.2%, which is about 60% greater than a typical response of a conventional device.

Figure 8 shows a response of another tunneling device of about 10 ohms in nominal R_J having the same material composition as the one described in Figure 7, but of different thickness. Here, the thickness of the

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CoFe, Al_2O_3 and NiFe layers are 80, 14, and 150 angstroms, respectively.

Figure 8 demonstrates that a significantly greater gain in JMR of about 30% can be achieved partly by
5 lowering the terminal junction resistance.

Similarly, Figure 9 shows a CoFe (100 Å)/ Al_2O_3 (16 Å)/Co (100 Å) device having large JMR in which a negative R_J is maintained throughout the magnetic field spectrum, which indicates that the parasitic resistive
10 effect, $f(R_L/R_T)$, dominates over the true junction resistance, R_T .

Figure 10 is a magnetic response of a CoFe (100Å)/AlN (18Å)/NiFe (27Å) trilayer junction device. In Figure 10, it is illustrated that a tunnel junction
15 can be made to operate as a switch by providing positive R_J in one magnetic field region and negative in another.

Figure 11 shows the memory effect of JMR of a preferred trilayer device. The junction is initially subjected to high field in one direction. Upon reducing
20 field level to zero and with a small applied field in the reverse direction ($-H_p$), the peak value of R_J is reached. Reducing the field level back to zero does not alter the peak value of R_J . This high value of R_J is stable and can be maintained even with a small positive
25 field excitation. Applying further field excitation in the forward direction to H_p decreases R_J and minor hysteresis loop is formed.

For the geometrically-enhanced tunneling device as depicted in Figures 3A to 3C, and the responses shown in
30 Figures 7 to 10, large JMR's can be realized by controlling the relative values of R_L and R_T . In particular, R_L can be varied by controlling the thickness or appropriately selecting the FM electrodes. Similarly, R_T can be varied by controlling the thickness
35 of the insulating layer. In a preferred embodiment, the FM film electrodes can range from about 10 angstroms to 1000 angstroms (1 to 100 nanometers), and the insulator

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barrier can be as thin as about 2 angstroms (0.2 nm), and as thick as about to 30 angstroms (3 nm).

Controlling the barrier thickness involves, inter alia, controlling the oxidation or nitriding duration in a vacuum evaporation or a sputtering process. For example, an oxidation by a glow discharge process can range anywhere from 2 to 110 seconds. Studies have shown that the junction resistance (R_T) is quite sensitive to the barrier thickness and changes nearly exponentially with respect to it. For example, the following shows is typical junction resistance range with respect to small variations in the barrier thickness:

	<u>barrier thickness, Å</u>	<u>R_T, Ω</u>
15	14	10K
	12	1K
	8	10

As shown, resistance drops considerably, for thinner barriers.

The magnetic field sensitivity of the tunneling devices can also be controlled by selecting appropriate FM materials having desired spin-polarization constants. The field sensitivity determines the amount of field strength required for a FM electrode to reverse its magnetization direction. By controlling the FM sensitivity, a device can be made to maintain a desirable hysteresis width for an application where such parameter is of importance.

Additionally, FM electrodes can be selected to control certain field response behavior. For example, Figures 19A to 19C illustrate field responses of tunnel devices, each device comprising FM electrodes of different combination of coercive field (H_C) values. Figure 19A is a response of a device in which the coercive force (H_{C1}) of a first electrode (FM_1) is significantly smaller than that (H_{C2}) of the second electrode (FM_2). The response in Figure 19A shows that

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the junction resistance is relatively insensitive to field changes. Figure 19B is a response of a device in which H_{c1} is nearly identical to H_{c2} , and shows that the change in junction resistance can be made quite
5 sensitive to a small change in field just by appropriately selecting FM electrodes of similar coercive properties. Figure 19C is a response of a device in which $H_{c1} \neq H_{c2}$, and where both H_{c1} and H_{c2} are quite large. Each application can require different
10 field constraints, and a designer can choose different FM combinations to satisfy such requirements.

From the above discussions, it is evident that in tunnel junctions where the lead resistance R_L contribution to the measured junction resistance R_j
15 becomes significant, the apparent JMR does not reflect the true percentage changes of the tunneling resistance. It is an artifact of the ill-defined four-terminal measurement in the cross geometry of the FM electrodes of the tunnel device. The current distribution is
20 inhomogeneous over the junction area when the two electrodes are perpendicularly crossed to form non-overlapping areas and R_L is comparable or greater than the true junction resistance R_T . Studies of known resistors show that R_j approaches R_T only when $R_T > 3R_L$.
25 In fact, when R_T/R_L ratio is 0.2 or below, R_j is close to zero or negative, respectively.

A preferred method of fabricating geometrically enhanced tunnel junctions includes a vacuum evaporation process in a chamber pressurized to about 8×10^{-8} Torr.
30 In the chamber, a silicon seed layer of about 1 nanometer (nm) in thickness is placed on a liquid nitrogen cooled glass substrate. The bottom ferromagnetic film strip, such as CoFe of about 10 nm in thickness, is deposited on the seed layer. Preferably,
35 the ferromagnetic films are deposited in the presence of about 100 Oe of applied magnetic field. In another preferred embodiment, a bottom ferromagnetic layer can

-19-

be prepared in room temperature without the silicon seeding layer. Applying magnetic field during the deposition stage improves the field sensitivity of the junction device. Figure 18 illustrates that the

5 junction 601, which was prepared in the presence of a nominal magnetic field undergoes resistive change at a significantly lower field excitation level than the similar field response for a device 603 formed in the absence of applied magnetic field.

10 An insulating layer, such as an aluminum metal film of preferred thickness of about 0.4 to 1.8 nm, overlays the bottom ferromagnetic film entirely. After warming the substrate to room temperature, the Aluminum layer is subjected to glow discharge to form an insulating tunnel

15 barrier. In the preferred embodiment, the glow discharge duration ranges from about a few to 110 seconds at a dc-bias of about 1 to 1.8 kV. The preferred overall thickness of the insulating layer ranges from a fraction of 1 nm to about 3 nm. As

20 discussed, the glow-discharge or sputtering duration impacts the overall insulator thickness which in turn controls the junction resistance. In general, the experiments have shown that nitriding the insulator layer, such as aluminum (i.e., AlN) results in a lower

25 junction resistance compared to oxidizing (i.e., Al_2O_3) for the same glow discharge conditions. In order to keep the contact surface of the first FM electrode clean and to avoid surface reaction, a very thin layer of insulating metal layer is left in the junction area.

30 Otherwise, a nearly perfect reactive treatment of the insulating metal film (such as Al, Mg, or Y) is required to leave no metal behind, to provide an "ideal" tunnel barrier, without reacting the surface of the first FM electrode.

35 The top ferromagnetic film of about 5 to 20 nm in thickness, such as Co or nickel iron ($\text{Ni}_{0.8}\text{Fe}_{0.2}$), is subsequently deposited in the presence of a nominal

-20-

field over the insulating barrier to form a cross geometry junction.

Other preferred methods of forming tunnel junction include various sputtering techniques to form the
5 ferromagnetic electrodes. These include radio frequency (RF), direct current (DC) magnetron, and ion-beam sputtering techniques. Similarly, a tunnel barrier can also be sputter-deposited with or without the presence of reactive gas. In another embodiment, sputtering and
10 vacuum evaporation methods can be combined to form tunneling devices. In this approach, the FM electrodes can be evaporated and the insulator sputter-deposited. Alternatively, the FM electrodes can be sputter-deposited and the barrier evaporated. A tunnel barrier
15 can also be partly evaporated and then reacted with gas, or partly sputtered.

As discussed above, selecting appropriate materials of desired electrical properties and thickness are important in controlling the junction resistance.
20 Appropriate insulating materials to form over the first FM electrode include aluminum (Al), magnesium (Mg), tantalum (Ta), titanium (Ti), yttrium (Y), and silicon (Si). Furthermore, sputtering or evaporation can be performed to form a composite insulating layer such as
25 aluminum oxide (Al_2O_3), aluminum nitride, silicon nitride, magnesium oxide, tantalum pentoxide, titanium oxide, yttrium oxide.

Preferred ferromagnet materials include CoFe, Co and nickel iron alloy ($\text{Ni}_{0.8}\text{Fe}_{0.2}$). For a conventional
30 ferromagnet or an alloy, the preferred polarization value is about 0.5 or less. Unconventional ferromagnets, such as half-metallic ferromagnets (HMF) can also be used in tunnel junctions. For example, nickel manganese antimony (NiMnSb) or platinum manganese
35 antimony (PtMnSb) can be used. For HMF's much higher polarization values, up to $p=1.0$, are afforded to yield greater JMR effects. Also, an HMF layer can be formed

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in combination with an FM layer to make a trilayer tunneling device as needed for various applications (i.e., HMF/I/FM or FM/I/HMF).

In another preferred embodiment, an anti-ferromagnetic compound, nickel oxide (NiO), is used to provide an exchange bias layer on an FM-I-FM tunnel junction. For example, a Co/Al₂O₃/Co FM-I-FM junction 620 includes a NiO layer 608 deposited over it as shown in Figure 20.

10 The interfacial coupling between the top FM layer (Co) 610 and the anti-ferromagnetic NiO film 608 creates an exchange bias effect. In other words, this effect shifts the junction magnetoresistance curves towards one side, making it asymmetric, especially on the H axis as
15 shown in Figure 21A. The steep rise in resistance with H indicated at 700 is moved closer to H = 0. This renders the device to respond near zero field and increases its sensitivity, thus allowing it to become more useful for applications such as sensors and read
20 heads.

The junction 620 comprises bottom FM layer 612, insulating barrier layer 614, and top FM layer 610. After the formation of the FM-I-FM junction, a layer 608 of NiO is deposited over top FM layer 610 *in-situ* in the
25 following manner. Ni metal is evaporated from an e-gun or a resistive filament with a directed flow of a small amount (1×10^{-4} to 1×10^{-6} Torr) of oxygen gas near substrate 622 (oxygen plasma will work more effectively). The substrate 622, with the FM-I-FM
30 junction already formed over it, is held at ambient temperature in general. Heating the substrate to temperatures up to 300°C during the growth of NiO is preferred. Ni evaporation is done slowly to provide desirable NiO film. However, using an oxygen plasma
35 near the substrate will allow faster growth of NiO. The thickness of the NiO film should be greater than 100Å in order to obtain good exchange biasing effect. An

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applied magnetic field greater than 10 Oe in the substrate plane is present during the NiO film growth.

In Figure 21A, the amount of shifting of the curve along the H axis is dependent on the growth conditions of NiO. Good interface (between the top FM layer 610 and the NiO layer 608) and heated substrates for NiO deposition will yield larger shift. Cooling the substrate back to ambient temperature is also done in the presence of the applied magnetic field. The exchange bias shift also increases when the sample temperature is lowered below room temperature as shown in Figure 21B. An NiO bias layer is superior to other materials such as FeMn, in that it is easier to prepare and is more corrosion resistant. Thus, NiO film not only provides the exchange bias medium but also acts as a protective coating for the FM-I-FM devices.

Figure 12 shows a memory storage device wherein a layer of a large number of FM-I-FM trilayer tunnel junctions 102 of the present invention are coated onto a disk surface 114 for storing a series of read-write binary data. Figure 13 is an enlarged view (top) of such a disk surface prior to applying the protective coating, where an individual FM-I-FM junction cell 300 is isolated from the other by a micro-thin insulator material 302. Figure 14 is a sectional view of the same disk surface (top half) which includes the layer of FM-I-FM junction 400 below a conducting layer 406, a protective coating 402 and an optional liquid lubricant layer 404. A layer 408 immediately below the trilayer junction is another conducting layer forming a closed-loop system. Below the second conducting layer is an electroless layer 410, and, finally, a substrate layer 412 underlies the entire structure. A group of such FM-I-FM junctions are arranged in a certain pattern to form a "sector", and a group of such sectors are arranged to form a "block". In Figure 12, each block or sector of data being written into or retrieved from the disk is

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particularly addressed for unrestricted access by the central processing unit (CPU) 121.

The memory device of the present invention is nonvolatile (data is maintained even when power is switched off). Furthermore, the resistive value of the trilayer junction, which represents a binary high ("1") or low ("0") can be maintained passively, requiring very little or no steady state external power. For example, a micro-coil 106 at the proximal end of a movable head 104 provides applied electromagnetic energy to affect the magnetization directions and to set the binary states of the individual sectors of FM-I-FM tunnel junctions. Once the binary states are set, the electromagnetic energy is no longer needed (i.e., switched off) to maintain such states. In a blown up view, the detail of this operation is illustrated in Figure 1, wherein the coil 16 provides magnetic field excitation similar to that of the micro-coil 106 in Figure 12. The application of electromagnetic energy in Figure 12 constitutes writing operation whereby the changes in resistance states of individual FM-I-FM junction cells correspond to a new entry of binary ones and zeroes.

A sensor head 124 near the proximal end of such movable head and adjacent to the micro-coil 106 performs a read operation by either measuring conductance or magnetic field across the FM-I-FM tunnel junctions. A read operation by measuring conductance can also be illustrated with the circuit in Figure 1. The sensor head of the present figure functions as the current source of Figure 1. By measuring the corresponding voltage drop, the resistance of a particular FM-I-FM junction cell can easily be determined. The positional head is controlled by a controller 120 and is coupled to an actuator device 110. The coupled unit comprising positional head and the actuator is then driven by a stepping motor 122. A data path 112 carries

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instructional signals and data exchanged between the CPU (central processing unit) and a disk interface 118 which channels information bits to appropriate devices in the system. The instructional signals include a set of
5 control signals routed to the controller for displacing the positional head. The instructional signals also include a signal to drive a high speed motor 116 coupled to the disk to displace the disk to a proper reading or writing orientation. A multi-output power supply 108
10 includes separate voltage lines to power the disk motor 116 as well as the stepping motor 122.

Figure 15 shows a high precision multi-sensor system 200 wherein an integrated circuit (IC) 206 comprises a plurality of FM-I-FM trilayer tunnel
15 junctions 212 of the present invention. Block 202 represents an arbitrary set of conditions (i.e., temperature, air pollutants, gas, etc.) being monitored by the system. A set of physical parameters corresponding to these conditions are quantified by a
20 sensor interface 222, and then electrically transduced by a signal transducer 204 into a particular range of magnetic field values. The FM-I-FM junctions are arranged to form a matrix array of information carrying bits, wherein each bit is either a binary "1" or "0".
25 Multiple-bit words (e.g., 8-bit, 16-bit, 32-bit etc.) are constructed as required to record and monitor physical conditions continuously. The information contained in the IC matrix is digitally sampled and decoded by a decoder 220. An output device 208
30 comprising a recording device 216 and a display device 218 processes decoded data in real time.

Figure 16A illustrates yet another embodiment of the present invention involving a high performance sensor. Figure 16A is a schematic of a portion of
35 magnetic storage disk drive using a sensor in accordance with the invention having a rotatable disk 502, a stepping motor 504, a position actuator 506, and a read-

-25-

write sensor head 508. The inset in Figure 16B shows an enlarged view of the read-write sensor head 508 comprising two FM-I-FM trilayer junctions 510 placed near the top and bottom surfaces of the disk. These surfaces of the disk are magnetically coated. Each of these magnetic surfaces is made up of cells representing bits of binary data. Each cell has a magnetization direction which is detectible by the sensor head (e.g., a cell having a high bit would cause to change the magnetization direction of the trilayer junction on the sensor head thereby creating a signal voltage). The actuator 506, coupled to the sensor head 508, moves the sensor head linearly or angularly across the disk surface to read or write binary information. The stepping motor 504 linearly drives the actuator. The sensor head made according to the present invention provides significantly improved signal-to-noise ratio at reduced weight, size and power consumption over the conventional heads. A sensor head comprising FM-I-FM junctions can easily be integrated into other forms of magnetic storage devices such as tape and floppy drives by replacing the existing read-write mechanism.

Figure 17A illustrates a medical imaging device which includes an array of magnetic sensor elements 100 for detecting a malignant cell or region of cells in a biological tissue sample 102. Each sensor element 100 of dimensions in the micron range comprises an FM-I-FM trilayer tunneling device of the present invention providing junction magnetoresistance (JMR) of greater than 10% (see Figure 17B). Preferably, each tunnel junction device is geometrically enhanced and is of low junction resistance to alleviate any noise problems associated with micron-level devices. The tissue sample 102 is pre-treated with magnetic coating which is absorbed by the healthy cells but otherwise non-absorbent by the cancerous or malignant cells. As shown in Figure 17C, the sensor elements 100 identify

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malignant cells by detecting any resistive change (i.e., JMR) registered by the individual tunneling device. Malignant cells are easily identifiable from the magnetic presence on these cells. The sensor signals
5 can be transmitted to a display station 104 for diagnosis. The diagnosis includes analyzing the magnitude of the sensor signals, corresponding to JMR, to identify the type and the severity of the cancerous cells. Additionally, the device of the present
10 invention can be implemented in a magnetic force microscope which is used as a detector to map out malignant regions in a larger biological tissue samples.

Equivalents

While the invention has been described in
15 connection with specific methods and apparatus, it is to be understood that the description is by way of example and not as a limitation to the scope of the invention as set forth in the claims.

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CLAIMS

What is claimed is:

1. A junction magnetoresistance system having a junction resistance comprising:
 - 5 a first electrode having a first independent magnetization direction;
 - a second electrode having a second independent magnetization direction;
 - an insulator between the first and second electrodes to form a trilayer tunnel junction
 - 10 having an effective junction resistance equal to the difference between the junction resistance and a parasitic resistance contributed by the electrodes near and throughout the junction;
 - 15 an electromagnetic source for applying electromagnetic energy to the junction, said energy reversing at least one of the magnetization directions of the first and second electrodes causing a change in the junction resistance by at
 - 20 least 10% at room temperature with respect to the effective junction resistance.
2. A device as claimed in Claim 1 further comprising electrical contacts connected to each of the first and second electrodes, wherein the first and second electrodes overlap in the junction, and the
- 25 contacts extend beyond the junction and are electrically continuous with the electrodes and form non-overlapping region with respect to the junction.
- 30 3. A device as claimed in Claim 1 wherein the first and second electrodes are ferromagnets.

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4. A device as claimed in Claim 3 wherein each of the ferromagnets has an electron spin polarization value of about 0.5 or less.
- 5 5. A device as claimed in Claim 1 wherein the first and second electrodes are half-metal ferromagnets.
6. A device as claimed in Claim 5 wherein each of the half-metal ferromagnets has an electron spin polarization value of about 1.0 or less.
- 10 7. A device as claimed in Claim 1 wherein one of the first and second electrodes is a ferromagnet and the other is a half-metal ferromagnet.
8. A device as claimed in Claim 1 wherein the parasitic resistance is controlled by varying the electrodes in thickness.
- 15 9. A device as claimed in Claim 1 wherein the parasitic resistance can be varied by selecting either of the first and second electrodes of a different electron spin polarization value.
- 20 10. A device as claimed in Claim 1 wherein the insulator layer ranges from about 2 angstroms to 30 angstroms in thickness.
11. A device as claimed in Claim 1 wherein the insulator comprises a metal film selected from a group consisting of Al, Mg, Ta, Ti, Y, and Si.
- 25 12. A device as claimed in Claim 11 wherein the insulator is formed by reacting the metal film with a reactive gas for a duration of about 2 to 110 seconds.

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13. A device as claimed in Claim 12 wherein the
junction resistance is controlled by varying the
insulator in thickness, the thickness of the
insulator being controlled by the reaction
5 duration.
14. A device as claimed in Claim 1 wherein the
insulator is a surface-reacted metal film selected
from a group consisting of Al_2O_3 , AlN , Si_3N_4 , MgO ,
 Ta_2O_5 , TiO_2 , and Y_2O_3 .
- 10 15. A device as claimed in Claim 1 wherein the
parasitic resistance is greater than the junction
resistance so as to render the effective resistance
negative.
- 15 16. A device as claimed in Claim 15 wherein the
effective junction resistance is initially negative
then changes to become positive when the
electromagnetic energy is applied to the junction.
17. A device as claimed in Claim 1 further comprising
an exchange biasing layer over the junction.
- 20 18. A device as claimed in Claim 17 wherein the
exchange biasing layer is nickel oxide.
19. A system for diagnosing biological tissue samples
comprising:
a sensor for detecting certain malignant
25 portions of a biological tissue sample pretreated
with a chemical coating including a magnetic
content which is essentially absorbed by healthy
portions of the sample and allows the sensor to
distinguish the healthy portions from the malignant
30 portions of the sample, said sensor including a

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matrix array of trilayer tunnel junction devices,
each device comprising:

a first electrode having a first
independent magnetization direction;

5 a second electrode having a second
independent magnetization direction; and

an insulator between the first and second
electrodes to form a trilayer tunnel junction
having an effective junction resistance equal to
10 the difference between the junction resistance and
a parasitic resistance contributed by the
electrodes near and throughout the junction,
wherein the magnetic contact of the sample provides
a magnetic field which reverses at least one of the
15 magnetization directions of the first and second
electrodes and causes a change in the junction
resistance by at least 10% at room temperature with
respect to the effective junction resistance; and

20 a display station connected to the sensor for
receiving image signals from the sensor to display
color-coded images of the sample to locate the
malignant portions of the sample.

20. A system as claimed in Claim 19 wherein the sample
is treated with a different chemical coating
25 including a magnetic content which is essentially
absorbed by the malignant portions of the sample,
and allows the sensor to distinguish the healthy
portions from the malignant portions of the sample.

21. A device as claimed in Claim 19 wherein the first
30 and second electrodes are ferromagnets.

22. A device as claimed in Claim 21 wherein each of the
ferromagnets has an electron spin polarization
value of about 0.5 or less.

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23. A device as claimed in Claim 19 wherein the first and second electrodes are half-metal ferromagnets.
24. A device as claimed in Claim 23 wherein each of the half-metal ferromagnets has an electron spin polarization value of about 1.0 or less.
25. A device as claimed in Claim 19 wherein one of the first and second electrodes is a ferromagnet and the other is a half-metal ferromagnet.
26. A device as claimed in Claim 19 wherein the insulator layer ranges from about 2 angstroms to 30 angstroms in thickness.
27. A device as claimed in Claim 19 wherein the insulator comprises a metal film selected from a group consisting of Al, Mg, Ta, Ti, Y, and Si.
28. A device as claimed in Claim 27 wherein the insulator is formed by reacting the metal film with a reactive gas for a duration of about 2 to 110 seconds.
29. A device as claimed in Claim 28 wherein the junction resistance is controlled by varying the insulator in thickness, the thickness of the insulator being controlled by the reacting duration.
30. A device as claimed in Claim 19 wherein the insulator is a surface-reacted metal film selected from a group consisting of Al_2O_3 , AlN, Si_3N_4 , MgO, Ta_2O_5 , TiO_2 , and Y_2O_3 .

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31. A computer storage device comprising:
a magnetic disk for storing binary data; and
a sensor-head for reading the data from the
disk comprising:
5 a first electrode having a first
independent magnetization direction;
a second electrode having a second
independent magnetization direction; and
an insulator between the first and second
10 electrodes to form a trilayer tunnel junction
having an effective junction resistance equal to
the difference between the junction resistance and
a parasitic resistance contributed by the
electrodes near and throughout the junction; and
15 an electromagnetic source for applying
electromagnetic energy to the junction, said energy
reverses at least one of the magnetization
directions of the first and second electrodes and
causes a change in the junction resistance by at
20 least 10% at room temperature with respect to the
effective junction resistance.
32. A device as claimed in Claim 31 wherein the first
and second electrodes are ferromagnets.
33. A device as claimed in Claim 32 wherein each of the
25 ferromagnets has an electron spin polarization
value of about 0.5 or less.
34. A device as claimed in Claim 31 wherein the first
and second electrodes are half-metal ferromagnets.
35. A device as claimed in Claim 34 wherein each of the
30 half-metal ferromagnets has an electron spin
polarization value of about 1.0 or less.

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36. A device as claimed in Claim 31 wherein one of the first and second electrodes is a ferromagnet and the other is a half-metal ferromagnet.
37. A device as claimed in Claim 31 wherein the
5 insulator layer ranges from about 2 angstroms to 30 angstroms in thickness.
38. A device as claimed in Claim 31 wherein the insulator comprises a metal film selected from a group consisting of Al, Mg, Ta, Ti, Y, and Si.
- 10 39. A device as claimed in Claim 38 wherein the insulator is formed by reacting the metal film with a reactive gas for a duration of about 2 to 110 seconds.
40. A device as claimed in Claim 39 wherein the
15 junction resistance is controlled by varying the insulator in thickness, the thickness of the insulator being controlled by the reaction duration.
41. A device as claimed in Claim 31 wherein the
20 insulator is a surface-reacted metal film selected from a group consisting of Al_2O_3 , AlN, Si_3N_4 , MgO, Ta_2O_5 , TiO_2 , and Y_2O_3 .
42. A method of forming a trilayer tunneling device comprising:
25 cooling a substrate in a vacuum;
 overlaying a thin seeding layer onto the substrate;
 depositing a first electrode onto the seeding layer;

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depositing an insulating layer onto the first electrode, the insulating layer having thickness ranging from about 2 angstroms to 30 angstrom; and
5 depositing a second electrode onto the insulating layer to form a region in which the first and second electrodes overlap and are separated by the insulating layer, said region providing a tunnel junction.

- 10 43. A method as claimed in Claim 42 wherein the first and second electrodes and the insulating layer are deposited by radio frequency magnetron sputtering.
44. A method as claimed in Claim 42 wherein the first and second electrodes and the insulating layer are deposited by direct current magnetron sputtering.
- 15 45. A method as claimed in Claim 42 wherein the first and second electrodes and the insulating layer are deposited by ion beam magnetron sputtering.
- 20 46. A method as claimed in Claim 42 wherein the insulating layer comprises a metal film selected from a group consisting of Al, Mg, Ta, Ti, Y, and Si.
- 25 47. A method as claimed in Claim 46 wherein the insulating layer is formed by reacting the metal film with a reactive gas for a duration of about 2 to 110 seconds.
- 30 48. A method as claimed in Claim 47 wherein the metal film is completely reacted by the reactive gas without causing reaction to the first electrode below, and leaving only molecules of the reactive gas as the insulating layer.

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49. A method as claimed in Claim 47 wherein an upper surface portion of the metal film is reacted with the reactive gas, leaving a lower portion of the metal film in contact with one side of the first electrode below.
50. A method as claimed in Claim 46 wherein the first and second electrodes and the metal film of the insulating layer are sputter deposited and the metal film is further reacted with a reactive gas by glow discharge.
51. A method as claimed in Claim 46 wherein the first and second electrodes and the metal film of the insulating layer are deposited by evaporation and the metal film is further reacted with a reactive gas by glow discharge.
52. A method as claimed in Claim 42 wherein the first and second electrodes are deposited in a presence of an applied magnetic field to improve magnetic field response characteristics of the tunnel junction.
53. A method as claimed in Claim 42 wherein the insulating layer is a surface-reacted metal film selected from a group consisting of Al_2O_3 , AlN , Si_3N_4 , MgO , Ta_2O_5 , TiO_2 , and Y_2O_3 .
54. A method as claimed in Claim 42 further comprising depositing an exchange biasing layer onto the second electrode.
55. A method as claimed in Claim 54 wherein the exchange biasing layer is nickel oxide.

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56. A method of detecting and diagnosing malignant portions of a biological tissue comprising:

pretreating a biological tissue sample with a chemical coating including a magnetic content which is essentially absorbed by healthy portions of the sample so as to distinguish the healthy portions from the malignant portions of the sample;

placing a sensor over the sample, the sensor including a matrix array of trilayer tunnel junction devices, each device comprising:

a first electrode having a first independent magnetization direction;

a second electrode having a second independent magnetization direction; and

an insulator between the first and second electrodes to form a trilayer tunnel junction having an effective junction resistance equal to the difference between the junction resistance and a parasitic resistance contributed by the electrodes near and throughout the junction;

allowing the magnetic content from the malignant portions of the sample to apply magnetic field energy to the sensor to cause each junction device to reverse at least one of the magnetization directions of the first and second electrodes and to cause a change in the junction resistance by at least 10% at room temperature with respect to the effective junction resistance; and

transmitting image signals from the sensor to a display station to display color-coded images of the sample to locate the malignant portions of the sample.

57. A system as claimed in Claim 56 wherein the sample is treated with a different chemical coating including a magnetic content which is essentially absorbed by the malignant portions of the sample,

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and allows the sensor to distinguish the healthy portions from the malignant portions of the sample.

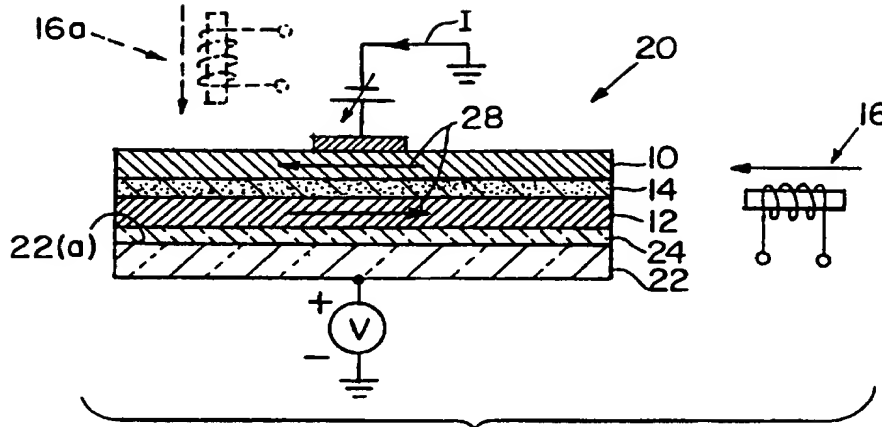


FIG. 1

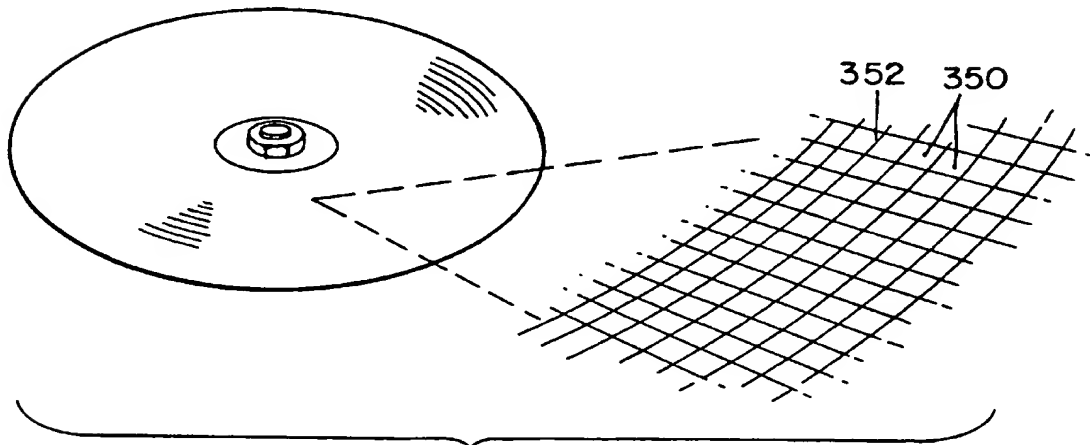


FIG. 13

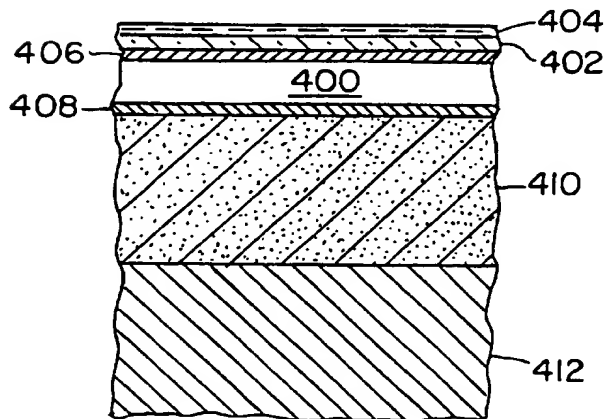


FIG. 14

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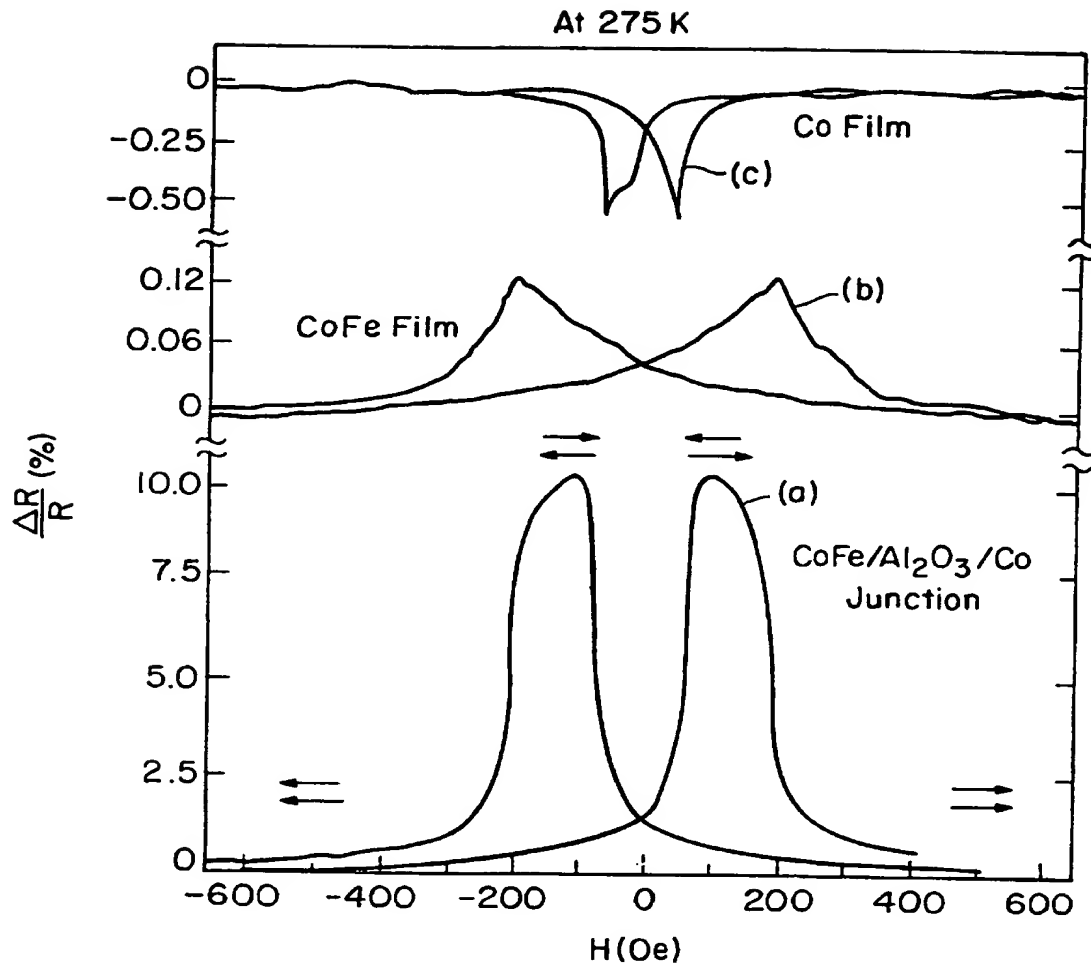


FIG. 2

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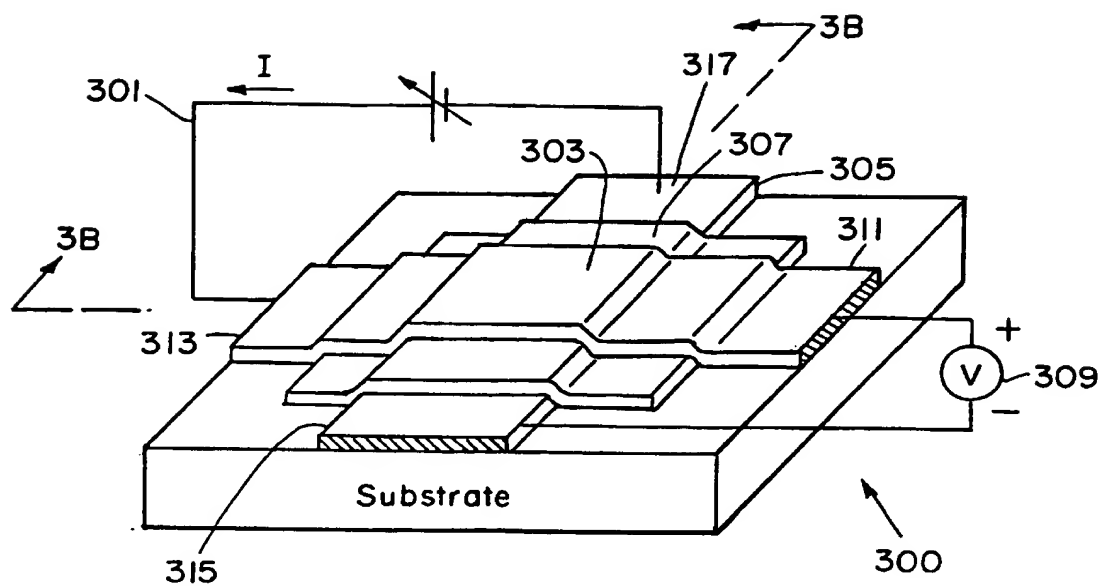


FIG. 3A

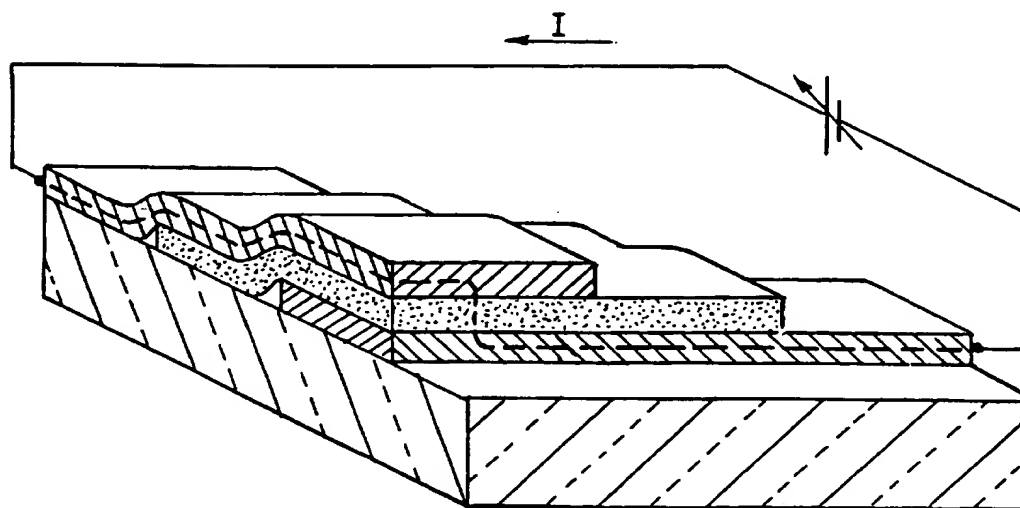
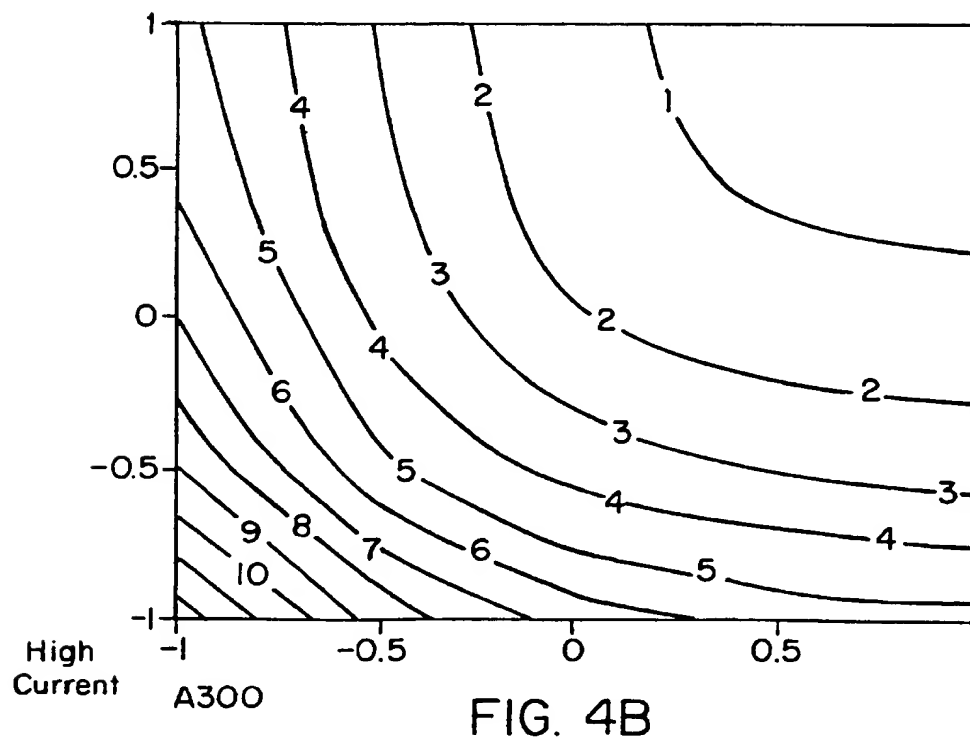
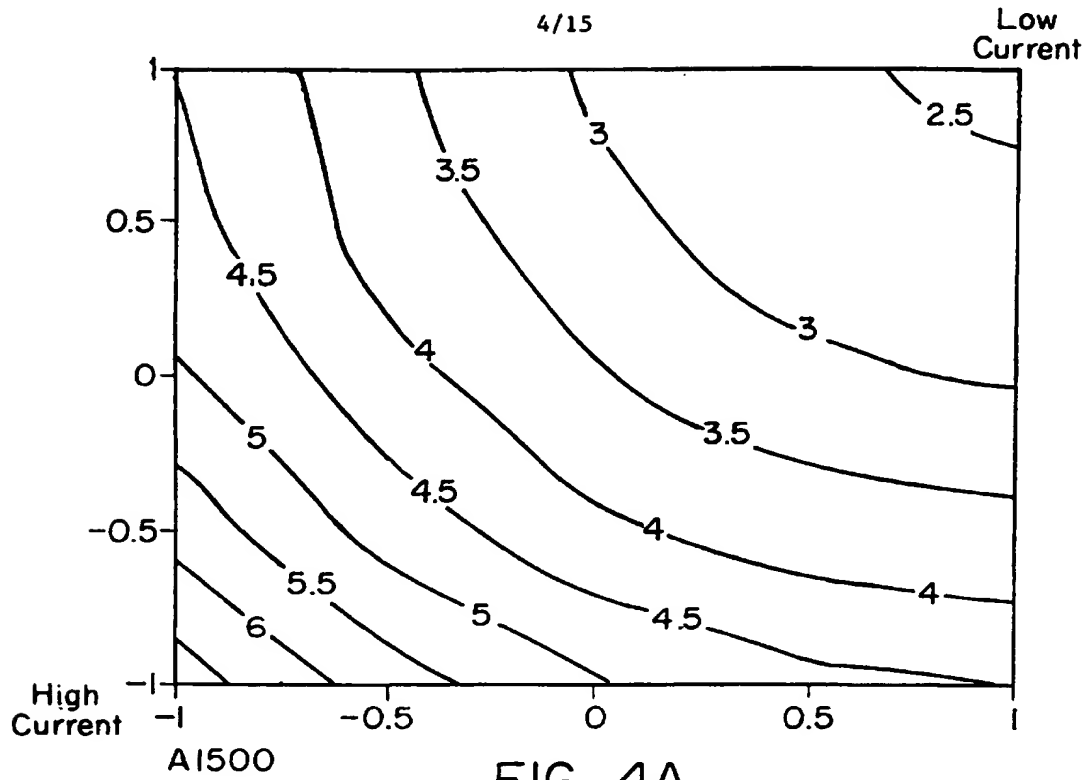


FIG. 3B



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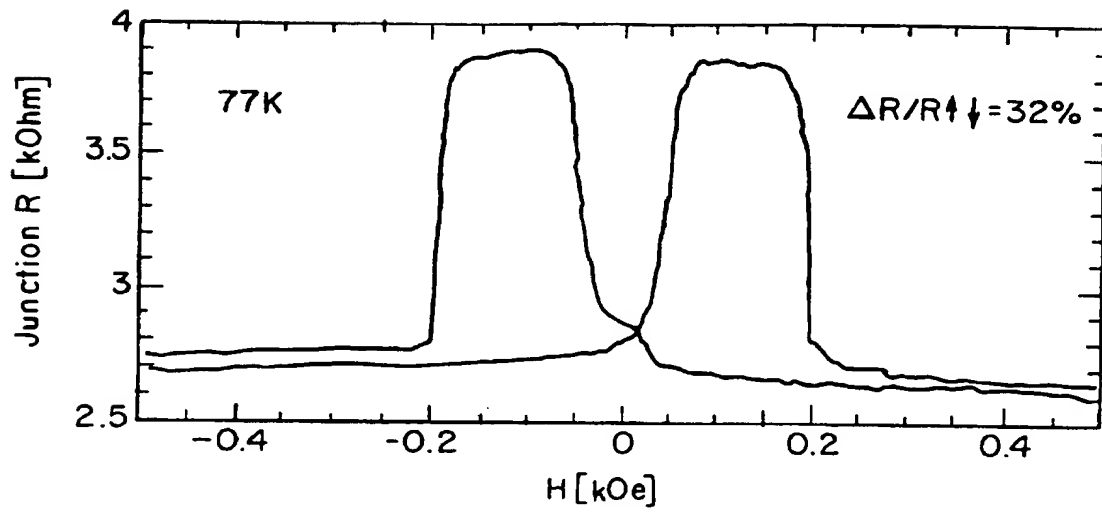


FIG. 5B

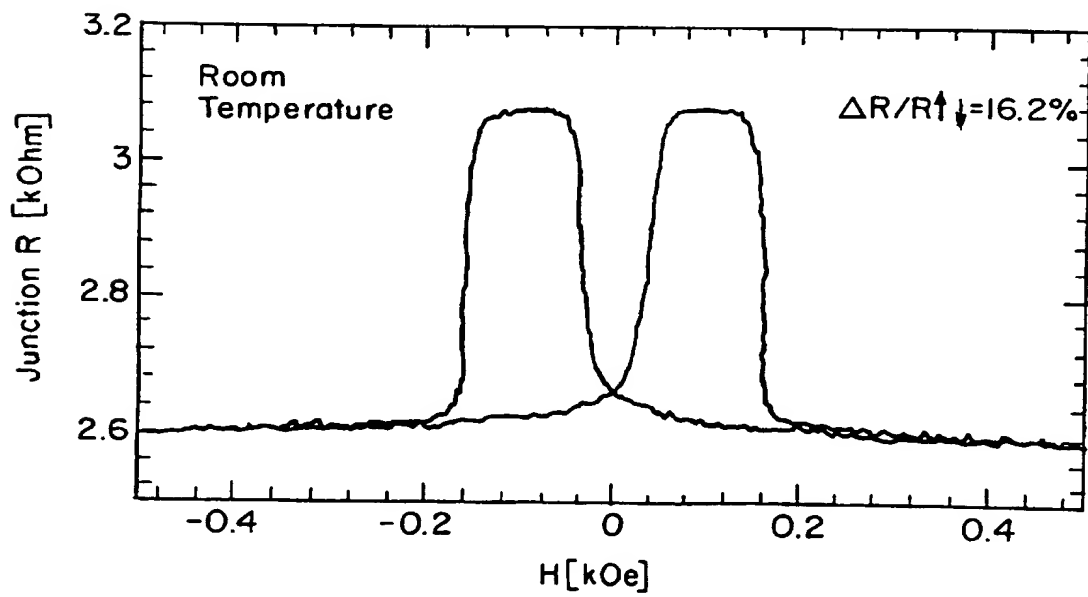


FIG. 5A

Possible Device Geometries

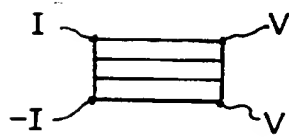
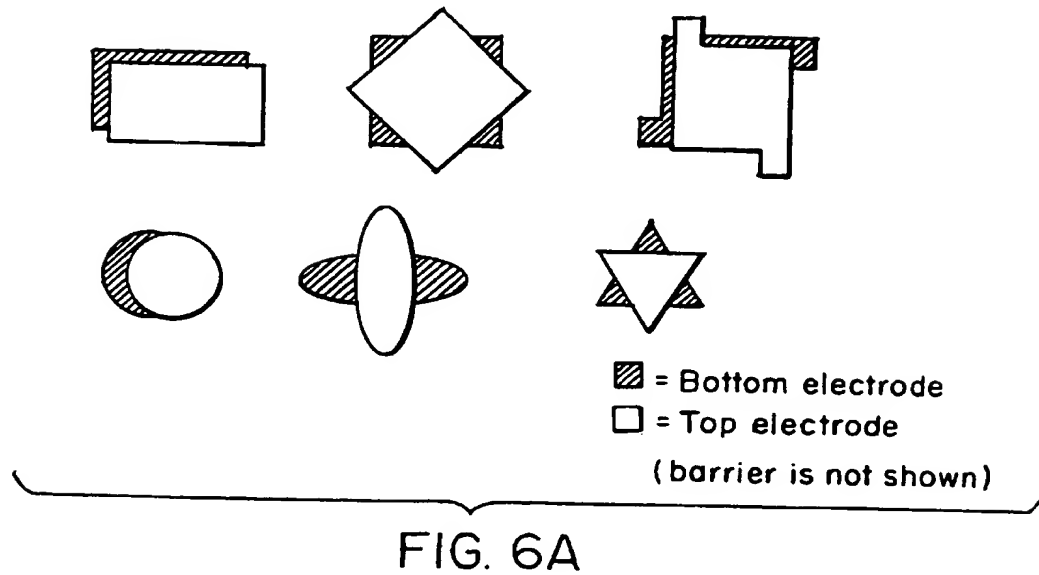


FIG. 6B

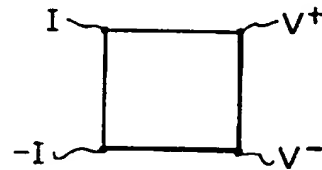


FIG. 6C

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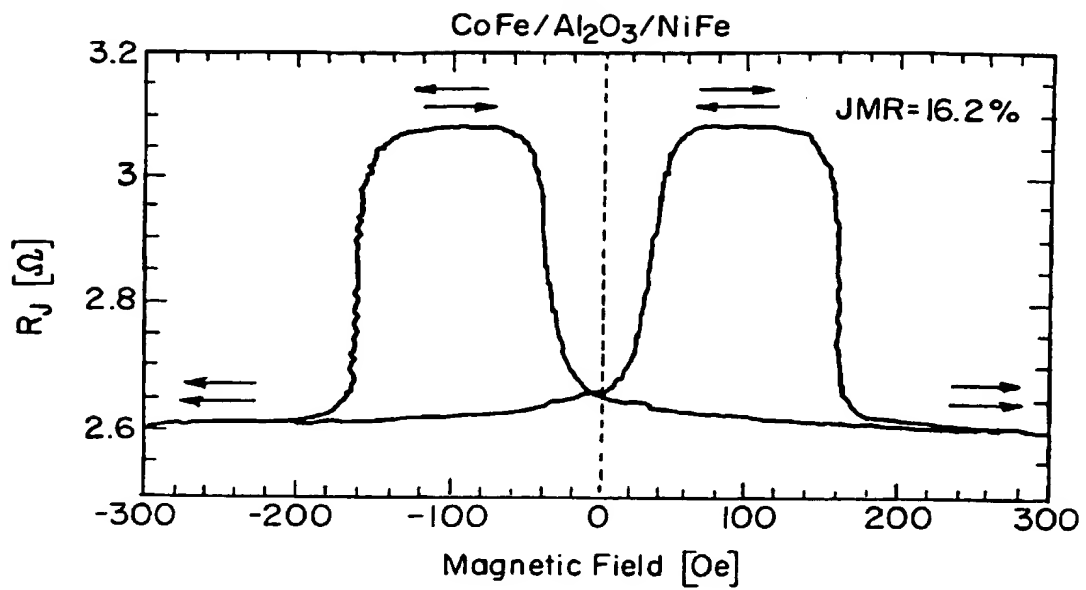


FIG. 7

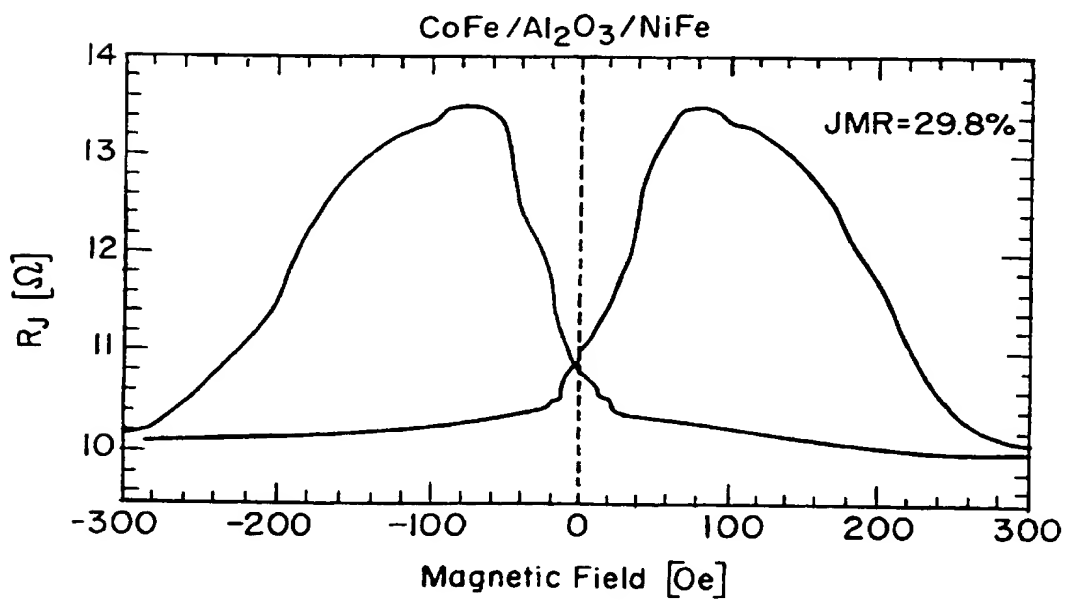


FIG. 8

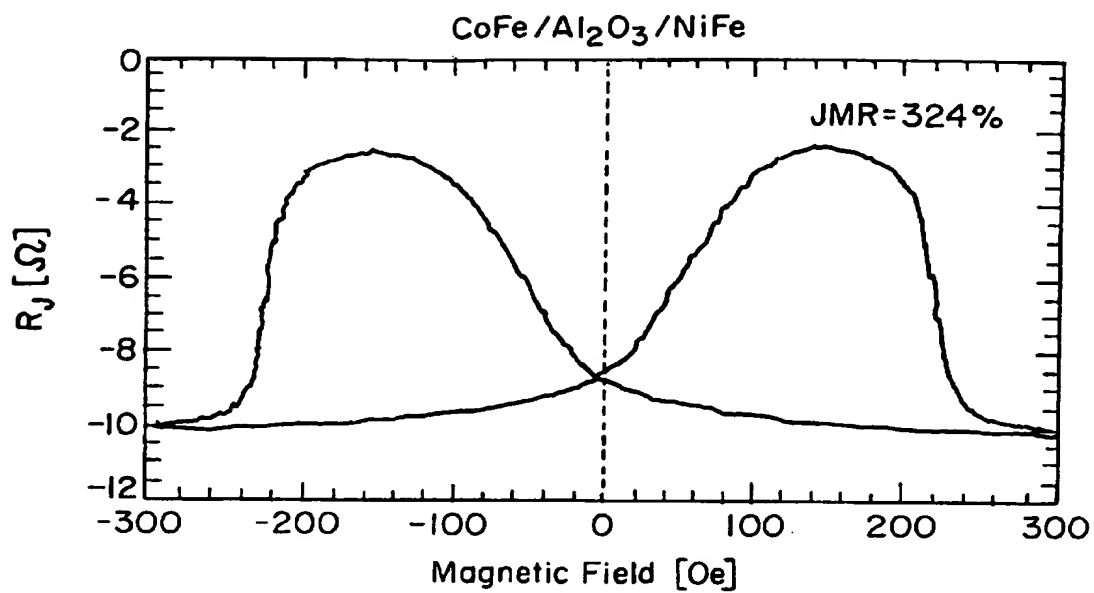


FIG. 9

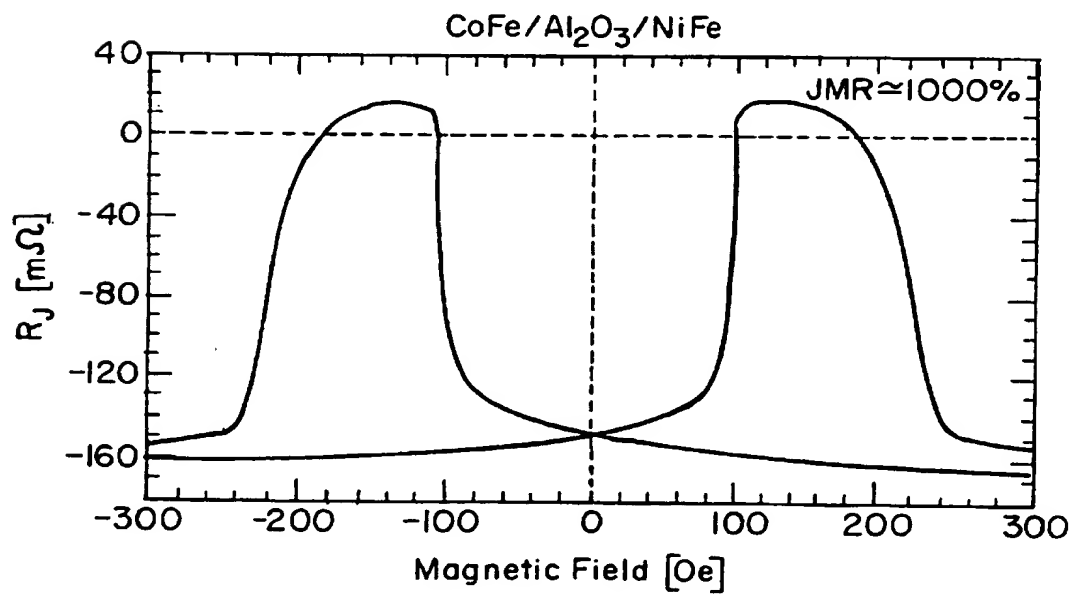


FIG. 10

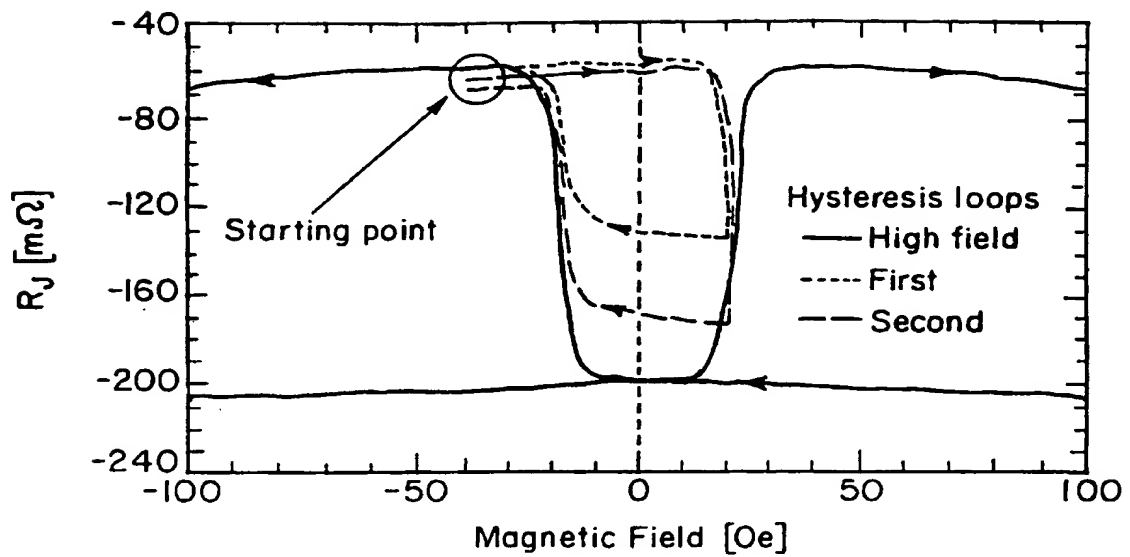


FIG. 11

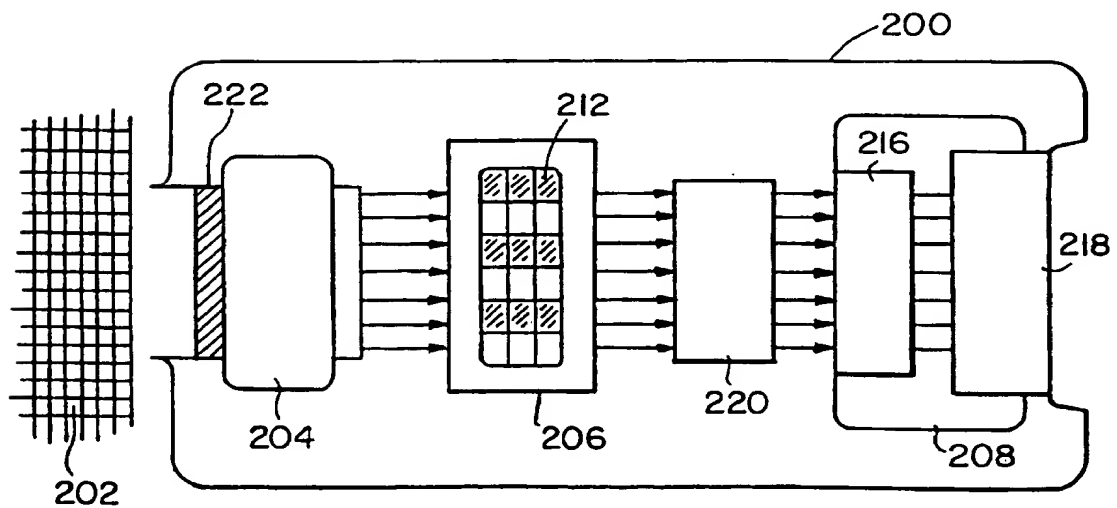


FIG. 15

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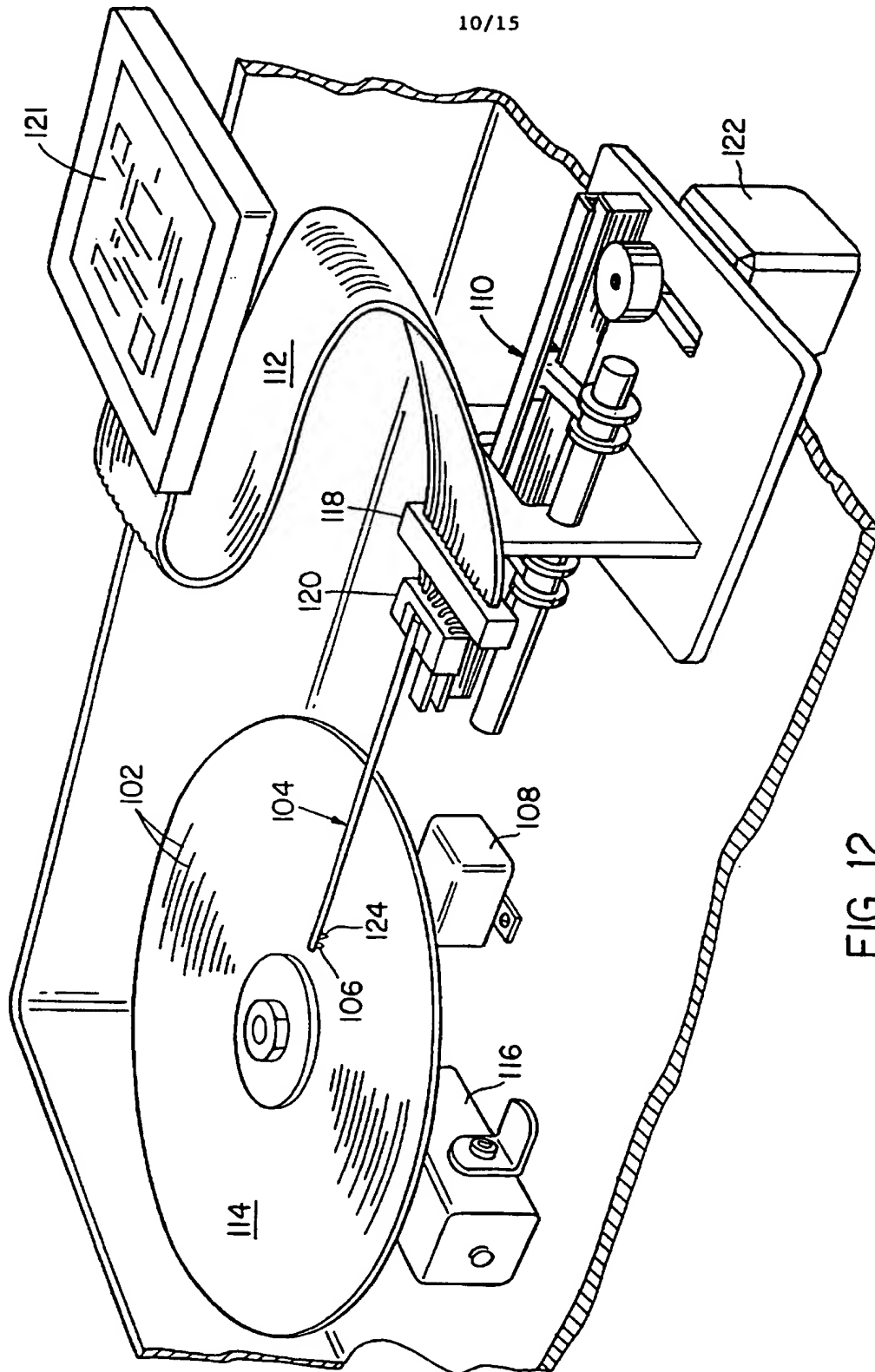
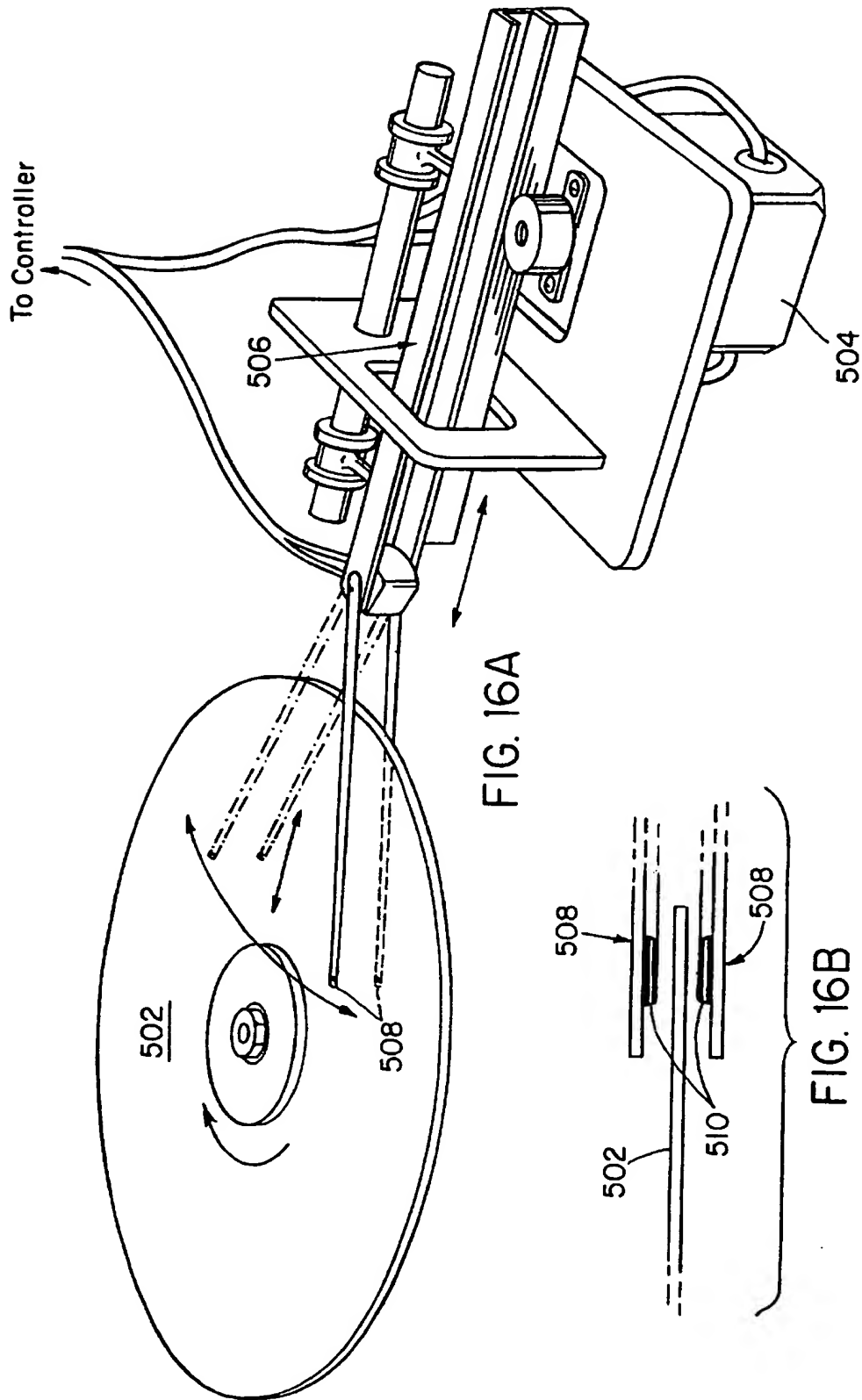


FIG. 12



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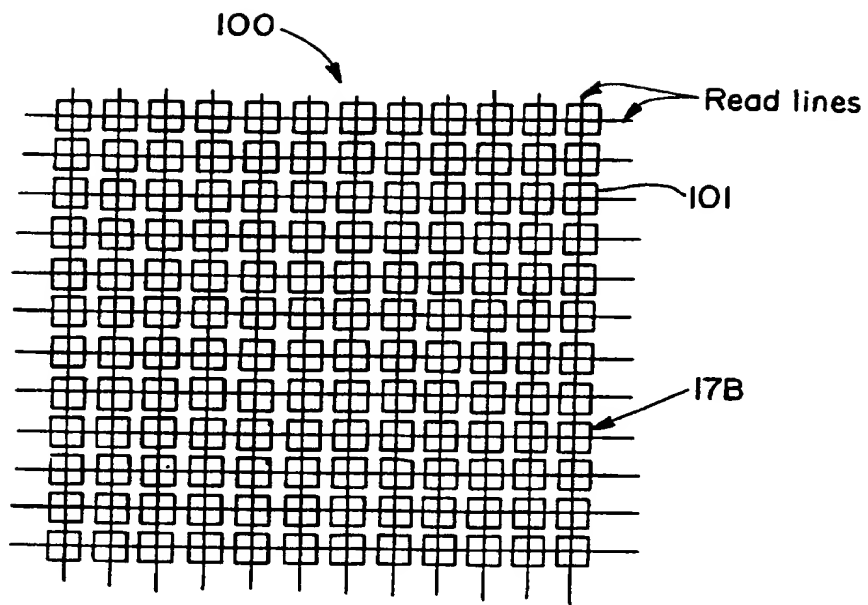


FIG. 17A

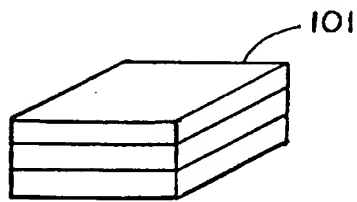


FIG. 17B

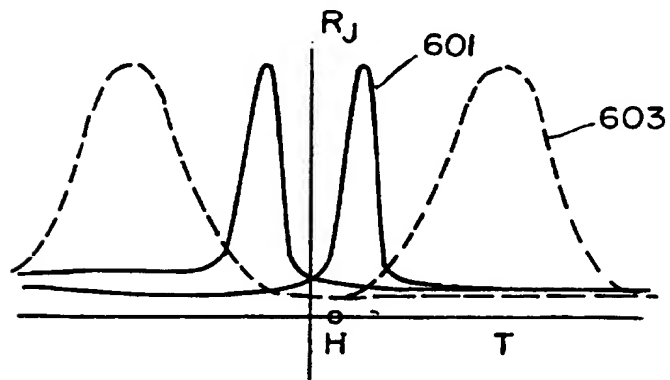
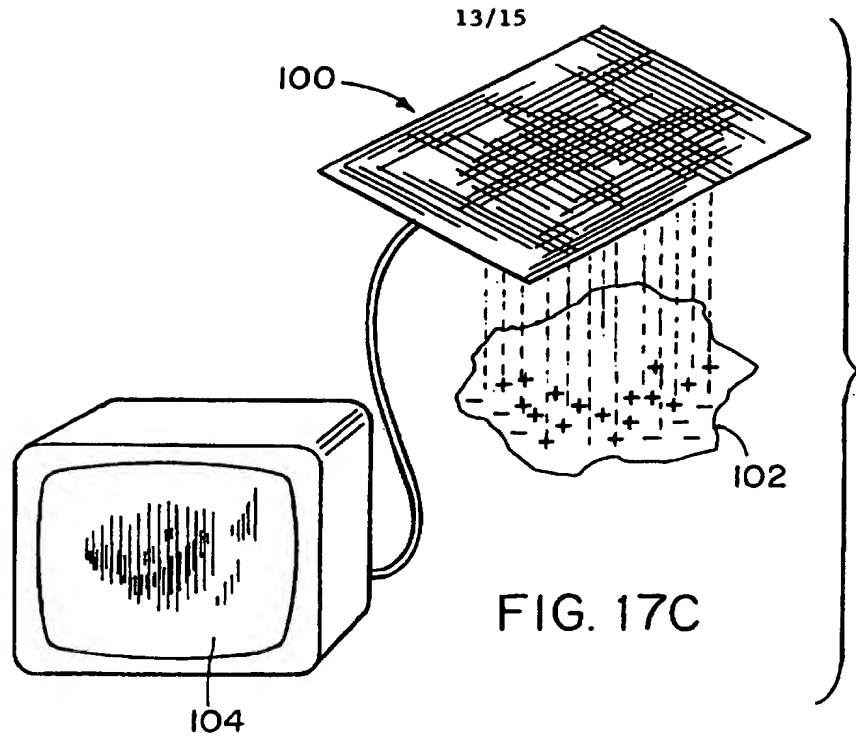


FIG. 18

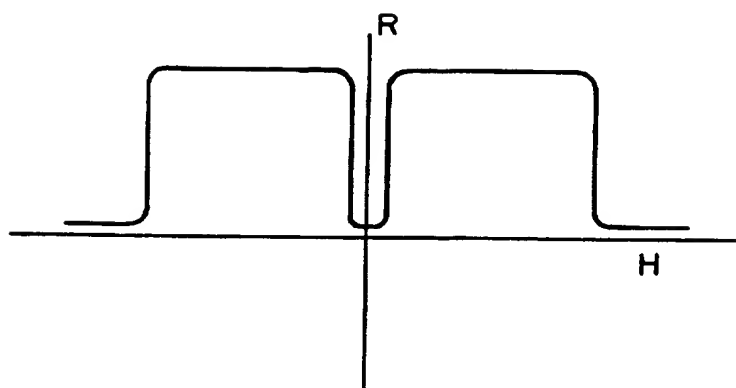


FIG. 19A

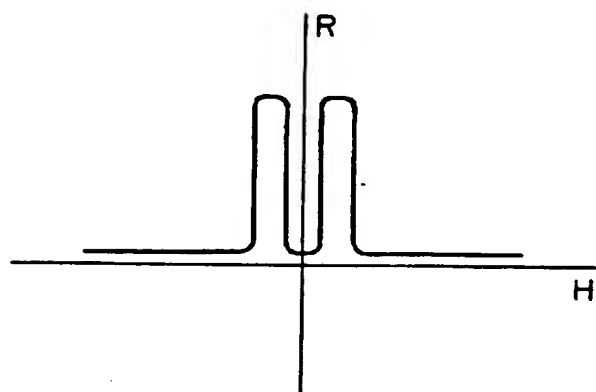


FIG. 19B

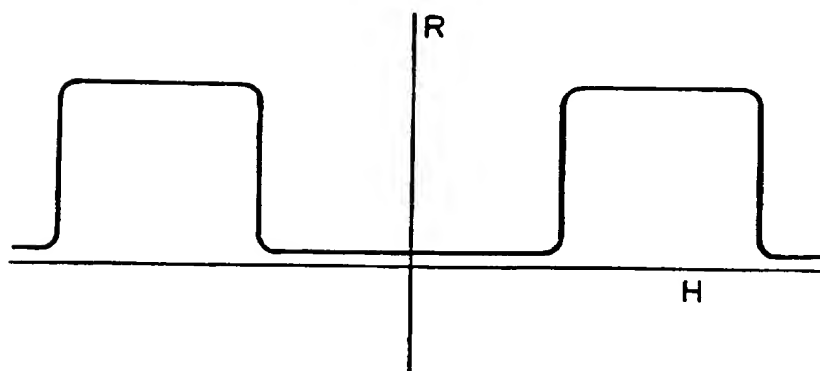


FIG. 19C

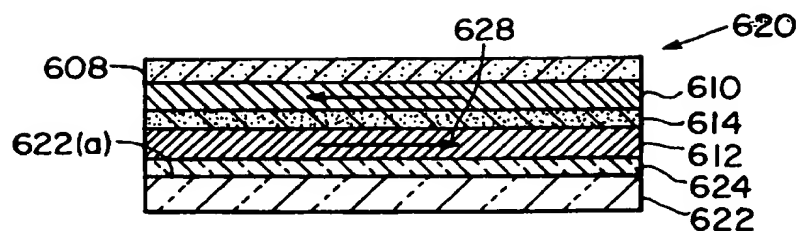


FIG. 20

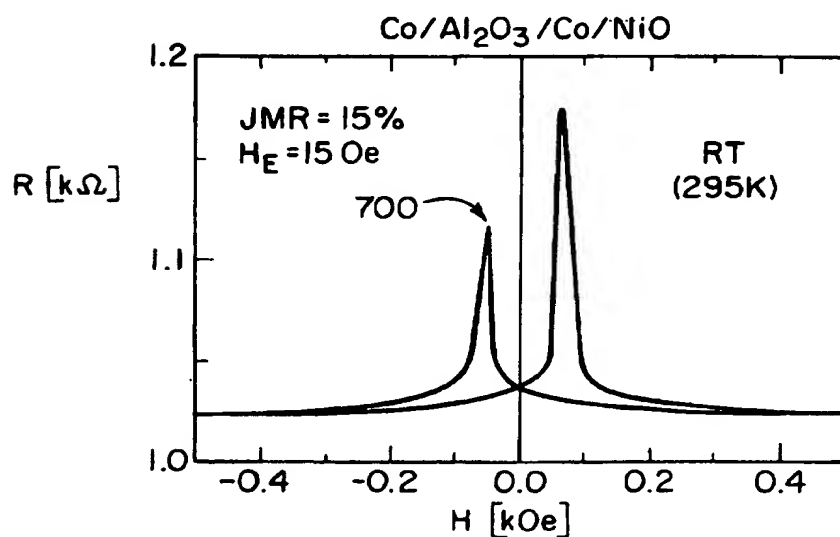
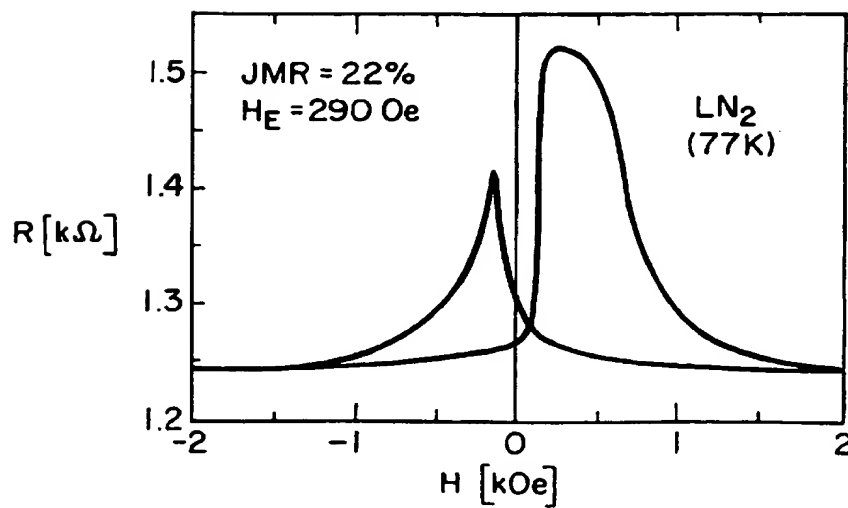


FIG. 21A

FIG. 21B
SUBSTITUTE SHEET (RULE 26)

INTERNATIONAL SEARCH REPORT

International Application No.
PC1/US 97/06247

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01L43/08 G11C11/15 A61B5/05

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01L H01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PHYSICAL REVIEW LETTERS, 17 APRIL 1995, USA, vol. 74, no. 16, ISSN 0031-9007, pages 3273-3276, XP002038207 MOODERA J S ET AL: "Large magnetoresistance at room temperature in ferromagnetic thin film tunnel junctions" see the whole document	1,3,4, 10,11, 14,42, 46,53
A	---	19-22, 26,27, 30-33, 37,38, 41, 48-51,56
	---	---

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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- *O* document referring to an oral disclosure, use, exhibition or other means
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- *&* document member of the same patent family

Date of the actual completion of the international search

20 August 1997

Date of mailing of the international search report

02.09.97

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Authorized officer

De Laere, A

INTERNATIONAL SEARCH REPORT

International Application No.
PC1/US 97/06247

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 95 10123 A (PHILIPS ELECTRONICS NV ;PHILIPS NORDEN AB (SE)) 13 April 1995 see page 1, line 1 - page 4, line 17 see page 7, line 20 - line 31. ---	1,3-7, 11, 17-19, 21-25, 27, 31-36,38
A	JOURNAL OF APPLIED PHYSICS, vol. 76, no. 10, PART 02, 15 November 1994, pages 6104-6106, XP000508715 PLASKETT T S ET AL: "MAGNETORESISTANCE AND MAGNETIC PROPERTIES OF NIFE/OXIDE/CO JUNCTIONS PREPARED BY MAGNETRON SPUTTERING" see the whole document ---	1-4,11, 14,15
A	PATENT ABSTRACTS OF JAPAN vol. 096, no. 007, 31 July 1996 & JP 08 070149 A (MITSUBISHI MATERIALS CORP), 12 March 1996, see abstract ---	1-4
P,X	APPLIED PHYSICS LETTERS, 29 JULY 1996, AIP, USA, vol. 69, no. 5, ISSN 0003-6951, pages 708-710, XP002038208 MOODERA J S ET AL: "Geometrically enhanced magnetoresistance in ferromagnet-insulator-ferromagnet tunnel junctions" see the whole document -----	1-4, 10-16, 42,46, 47,51-53

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/US 97/06247

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9510123 A	13-04-95	EP 0672303 A JP 8504303 T	20-09-95 07-05-96
